Short-Baseline Neutrino Oscillation Program on the Fermilab Booster Neutrino Beam

Fermilab Neutrino Seminar

December 4th 2014

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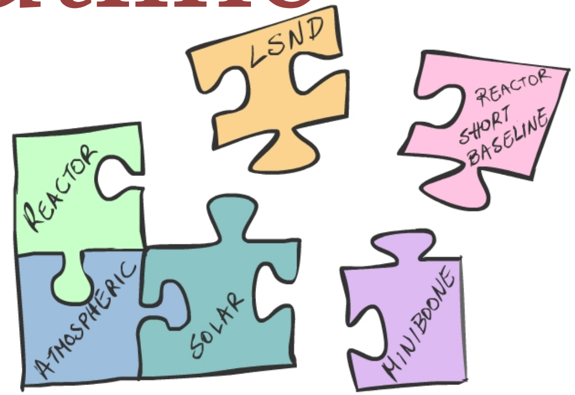
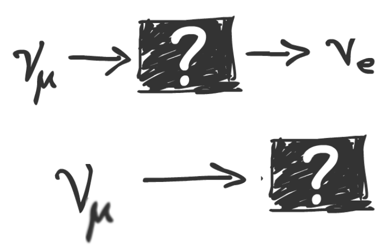
*on leave of absence from Laboratori Nazionali del Gran Sasso, Italy

Outline



- Motivation
- Brief History:
  - LAr1-ND, ICARUS Proposals
- Current status of the Fermilab Short-Baseline Neutrino Program
- The MicroBooNE, LAr1-ND and ICARUS Detectors
- Physics Reach
- Conclusions

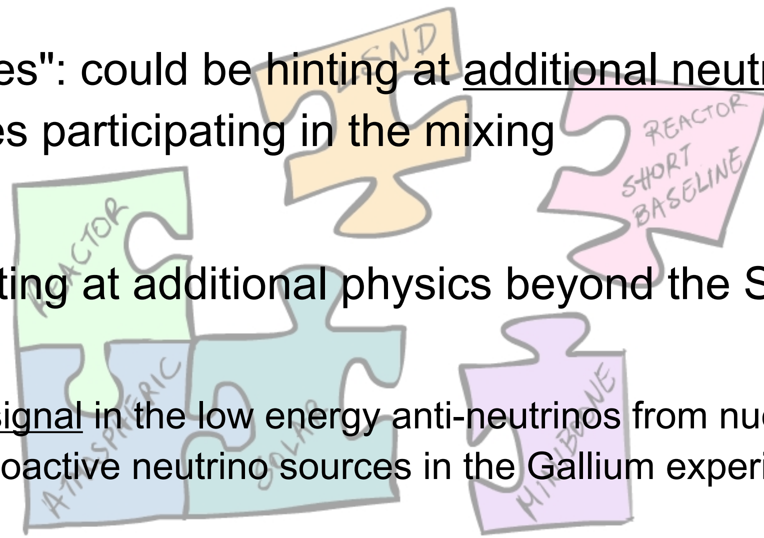


Neutrino Anomalies and Sterile Neutrinos

- Experimental observations of neutrino oscillations: picture consistent with the mixing of <u>3 neutrino flavors</u> with <u>3 mass eigenstates</u> (with relatively small mass differences

$$\Delta m^2_{31} \simeq 2.4 \cdot 10^{-3}\ \mathrm{eV}^2 \text{ and } \Delta m_{21} \simeq 7.5 \cdot 10^{-5}\ \mathrm{eV}^2$$

- Several experimental "anomalies": could be hinting at <u>additional neutrino states</u> with larger mass-squared differences participating in the mixing



- Two classes of anomalies pointing at additional physics beyond the Standard Model in the neutrino sector:

  a) the apparent <u>disappearance signal</u> in the low energy anti-neutrinos from nuclear reactors (the "<u>reactor anomaly</u>") and from radioactive neutrino sources in the Gallium experiments (the "<u>Gallium anomaly</u>")

  b) evidence for an <u>electron-like excess</u> in interactions coming from neutrinos from particle accelerators (the "<u>LSND and Mini-BooNE anomalies</u>")

- None of these results can be described by oscillations between the 3 Standard Model neutrinos and could be hinting at important <u>new physics</u> with the possible existence of at **least one fourth non-standard neutrino state** - driving oscillation at small distances $\Delta m^2_{new} \geq 0.1\ \mathrm{eV}^2$

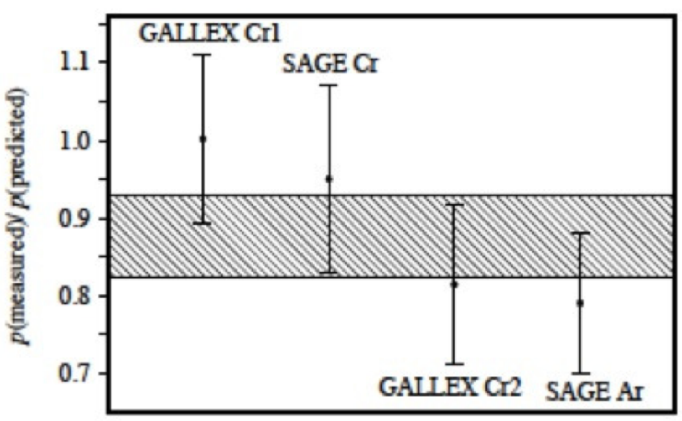
Experimental Hints for beyond 3 neutrino mixing a)

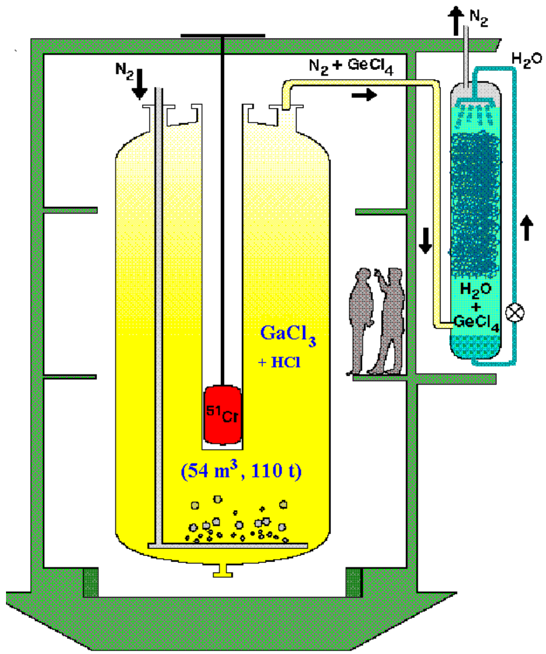
- A possible <u>electron anti-neutrino disappearance</u> signal has been observed a few meters away from nuclear reactors in the form of a deficit in the detected event rates compared to the predicted rates

  R = 0.938±0.023 2.7σ deviation from R=1

- A similar indication for <u>electron neutrino disappearance</u> by the SAGE and GALLEX solar neutrino experiments measuring the calibration signal produced by intense k-capture sources of ^{51}Cr and ^{37}Ar. Combined ratio between the detected and the predicted neutrino rates

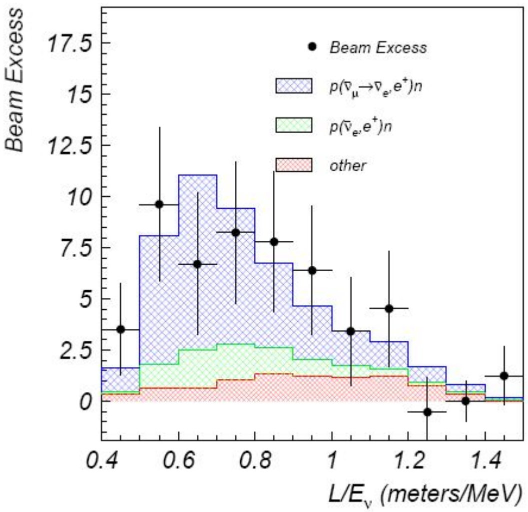
  R = 0.86±0.05 2.7σ significance from R = 1





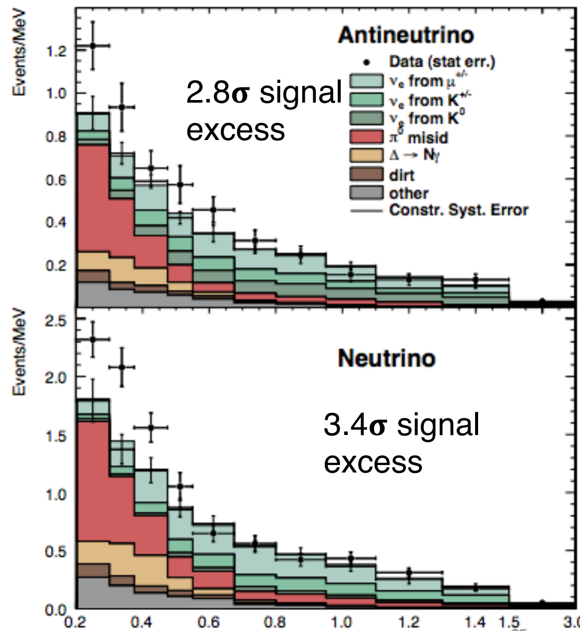
Experimental Hints for beyond 3 neutrino mixing b)

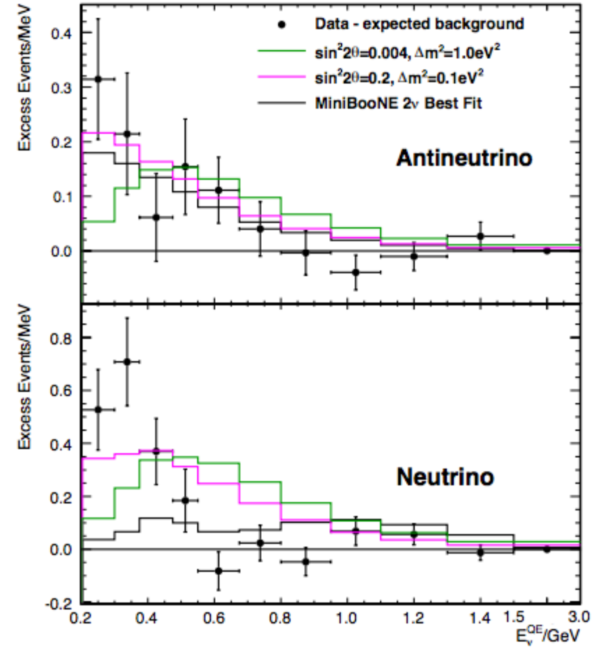
LSND : Excess of electron anti-neutrino candidate events



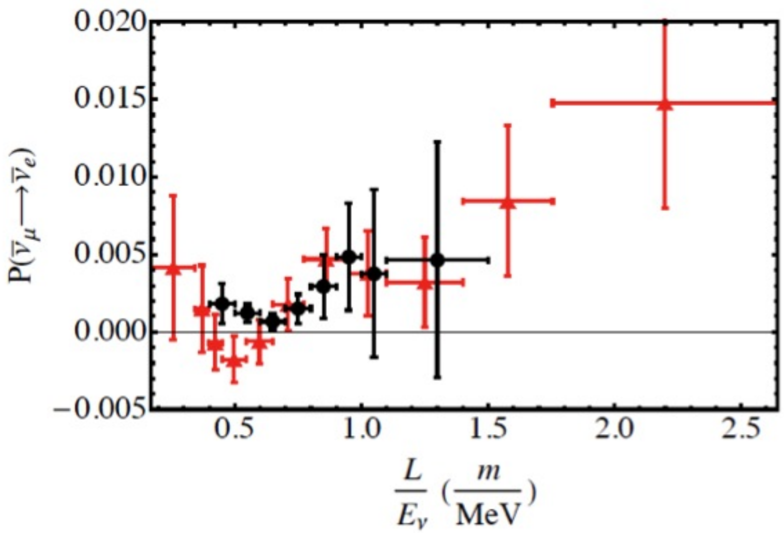
MiniBooNE: Excess of electron (anti-)neutrino candidate events

A. A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. 110 161801 (2013)





L/E dependence of the **MiniBooNE** anti-neutrino events and **LSND** events



The excess events can be electrons or single photons since these are indistinguishable in MiniBooNE's Cherenkov imaging detector

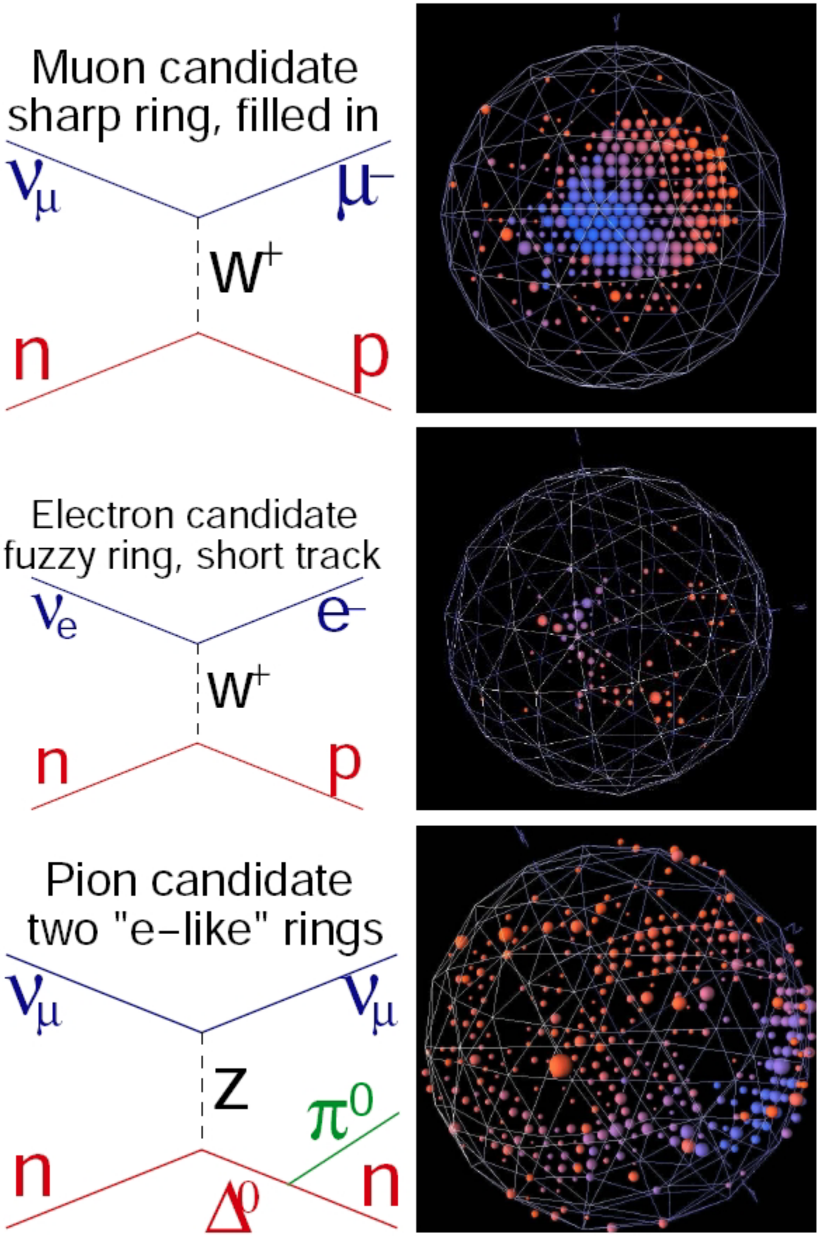
MiniBooNE: Cherenkov detector

- Cherenkov detector - see Cherenkov light rings generated by charged particles
- Looking for:

$$\nu_\mu \rightarrow \nu_e$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

- Backgrounds come from small intrinsic ν_e rate in the beam and any ν_μ interactions that leave a single reconstructed photon in the final state
- Cherenkov detector can not distinguish electron from single gamma



The Current Experimental Landscape

Radioactive sources | *Reactors*

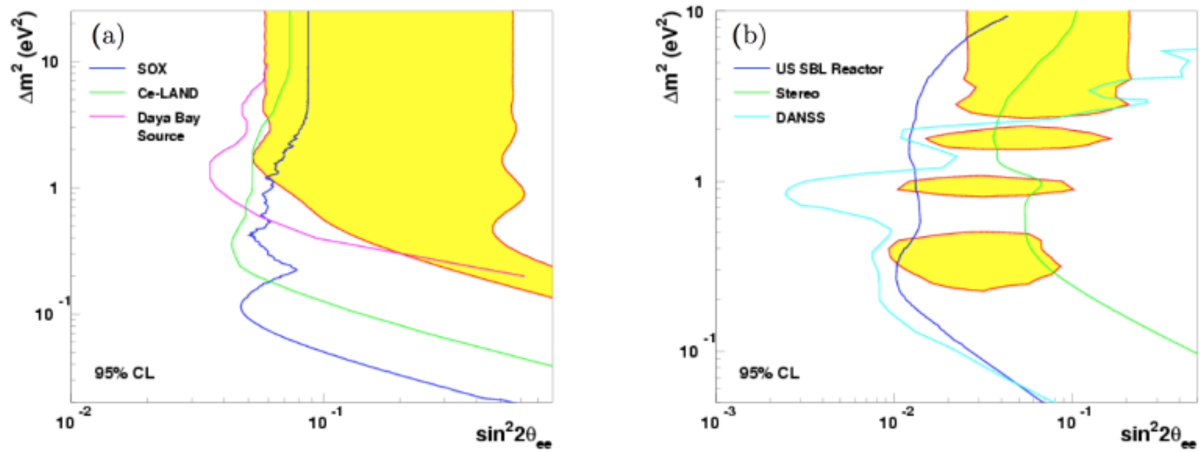


FIG. 9: *Expected sensitivity curves at 95% C.L. for proposed neutrino experiments with radioactive sources (a) and reactors (b) against the global fits for the gallium anomaly and reactor anomaly (yellow regions) [21].*

KATRIN (search for a distortion at the high energy endpoint of the electron spectrum of tritium β-decay)

IsoDAR (high power low energy cyclotron to produce anti-ν_μ from the -decay of ^{8}He)

OscSNS (800-ton gadolinium-doped scintillator detector @ the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory). Well-understood source of electron and muon neutrinos from π and decays-at-rest.

nuSTORM (muon storage ring@ FNAL or CERN)

Accelerator-based decay-in-flight (DIF) neutrino source - BNB at FNAL

The Current Experimental

Radioactive sources

Reactors

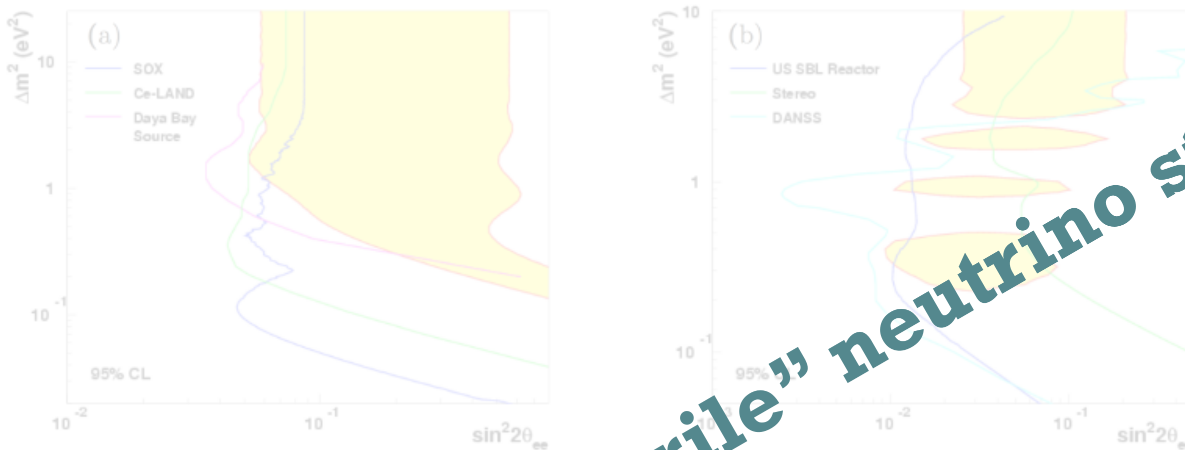


FIG. 9: *Expected sensitivity curves at 95% C.L. for proposed neutrino experiments with radioactive sources (a) and reactors (b) against the global fits for the gallium anomaly and reactor anomaly (yellow regions) [21].*

Are there additional, “sterile” neutrino states?

KATRIN

IsoDAR

OscSNS

at the Oak Ridge National Laboratory). Well-understood source of electron and muon neutrinos from

nuSTORM

Accelerator-based decay-in-flight (DIF) neutrino source

Booster Short Baseline Neutrino Beam

BNB at FNAL is a well established existing beamline:

- Robust target and horn system
- BNB neutrino fluxes well understood due to dedicated hadron production data (HARP experiment @ CERN) and 10+ years of study by MiniBooNE and SciBooNE
- Fermilab is taking the next step on this front with the MicroBooNE experiment nearing data taking
- Beam near surface (~10m) => modest civil construction cost

Fermilab neutrino beams

History

- Summer 2012 - LOI submitted to the Fermilab PAC for the "LAr1" project
  - 1-kton FV LAr TPC, based on designs for LBNE. Estimated cost was $80M
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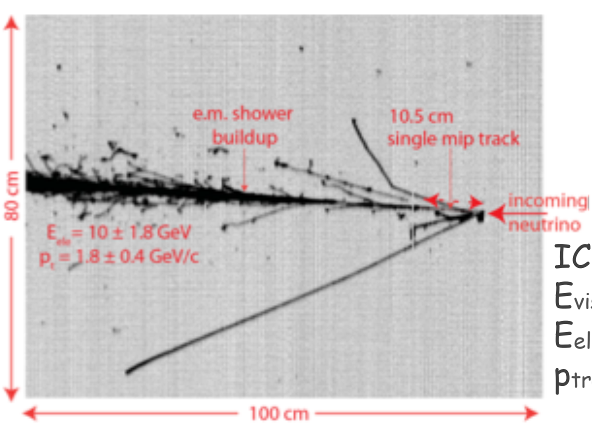
  - P-1052: ICARUS@FNAL
    - Propose relocating an updated ICARUS T600 LAr TPC detector to the BNB as far detector and construct new ¼ scale (T150) detector with same design to serve as a near detector for oscillation searches.

P-1052: ICARUS at BNB

- ICARUS T600 detector located along the BNB at ~700m from the target
- New T150 detector based on T600 design located at 150±50m from target

- T600 would also receive ν's from the off-axis NuMI neutrino beam peaked at ~2 GeV with an enriched ν_e flux



ICARUS data event with:
$E_{visible}$ = 11.5 ± 1.8 GeV
$E_{electron}$ = 10 ± 1.8 GeV
$p_{transverse}$ = 1.8 ± 0.4 GeV/c

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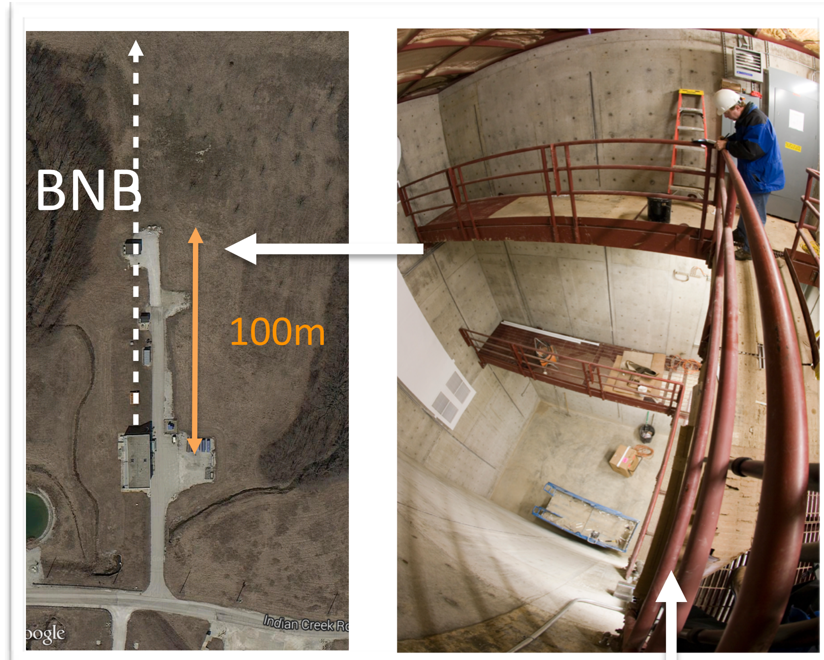
P-1053: LAr1-ND

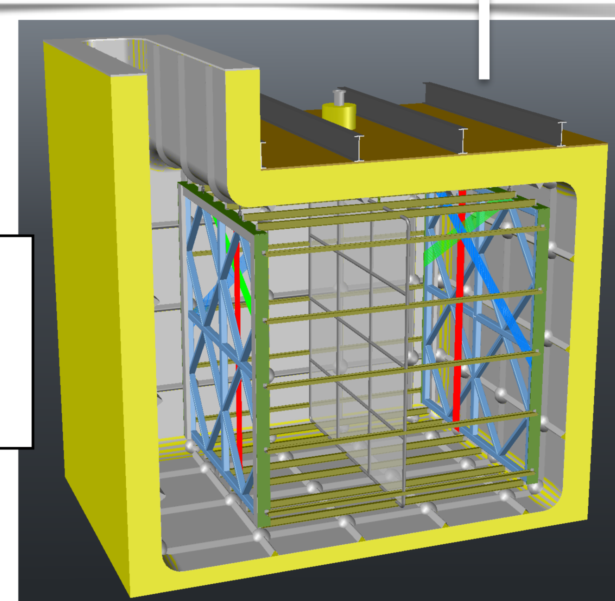
- New LAr TPC detector
  - Utilize LBNE far detector design concepts as much as feasible
    ➜R&D benefit for LBN program
  - Build on experience of T600, MicroBooNE, LBNE 35 ton
  - Locate at 100m in existing SciBooNE enclosure ➜ cost control



- High statistics measurement of intrinsic BNB ν content, combine with far detector

- With MicroBooNE, provide a complete interpretation of the MiniBooNE excess: γ or e? Intrinsic or appearing?

- “Physics R&D”: Reconstruction development and GeV ν-Ar cross sections.



82 ton TPC membrane cryostat design

~1M ν_μ events per year, 6,000 ν_e per year!

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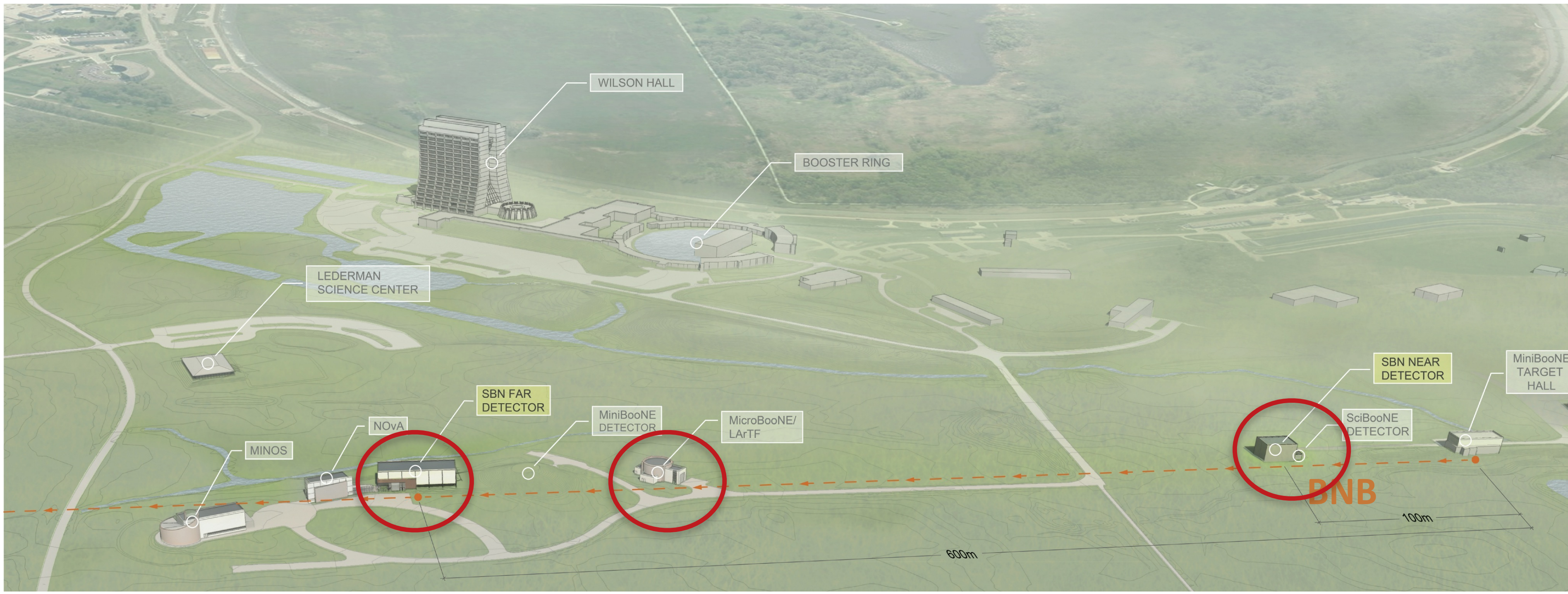
➔ **SBN Oscillation Program**

<u>July 2014: the LAr1-ND experiment is approved (T-1053)</u>

SBN Experimental Program

The future short-baseline experimental configuration is proposed to include three LArTPCs located on-axis in the BNB.

Multiple detectors very valuable for reducing systematic uncertainties.



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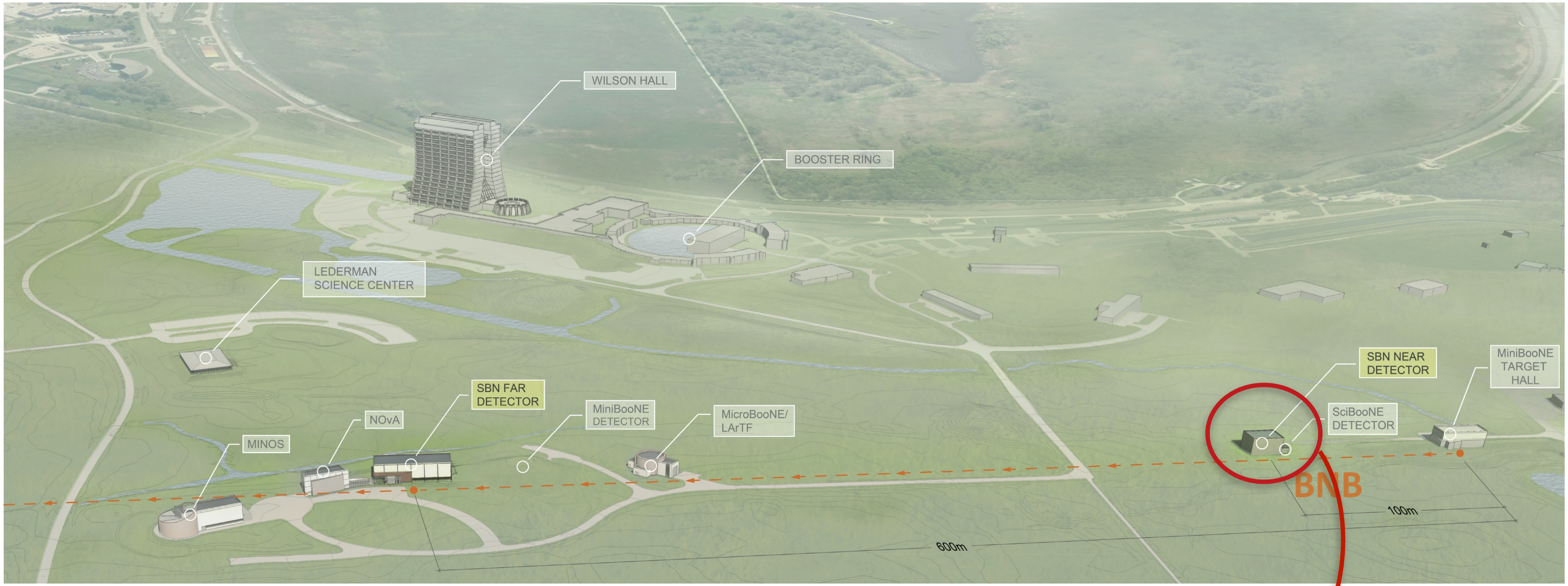

The <u>near detector (LAr1-ND)</u> will be located in a new building directly downstream of the existing SciBooNE enclosure 110 m from the BNB target

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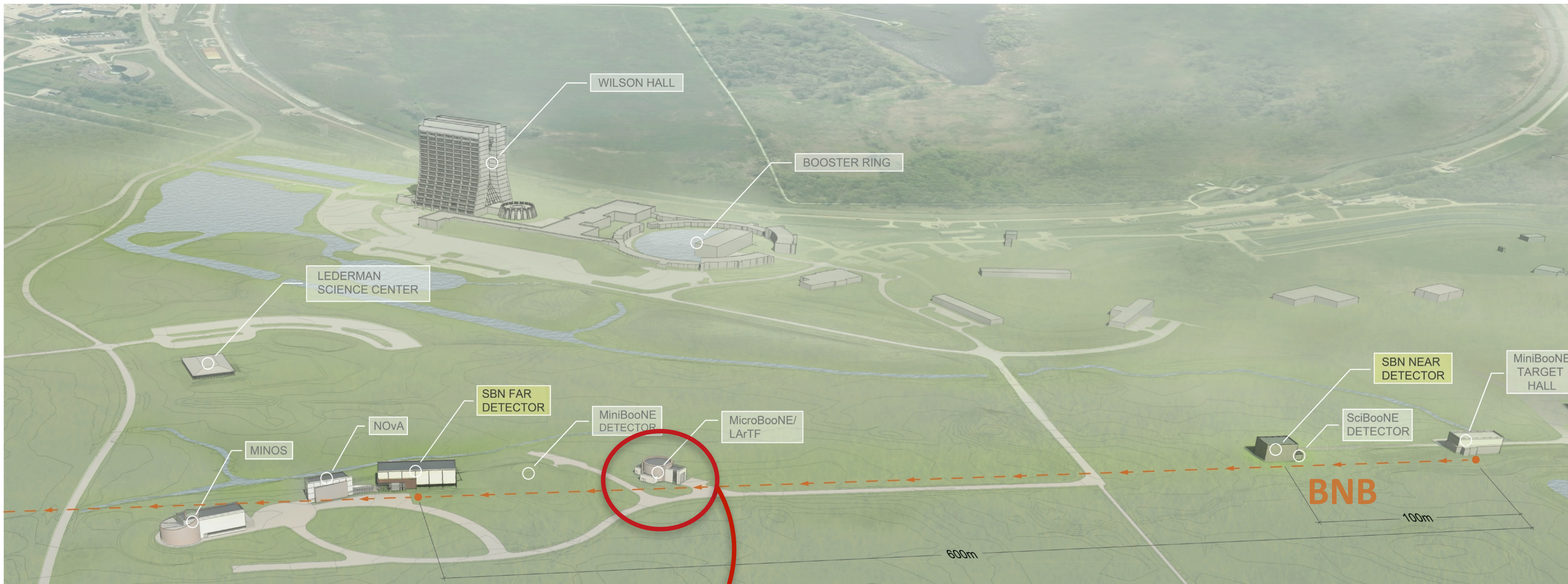

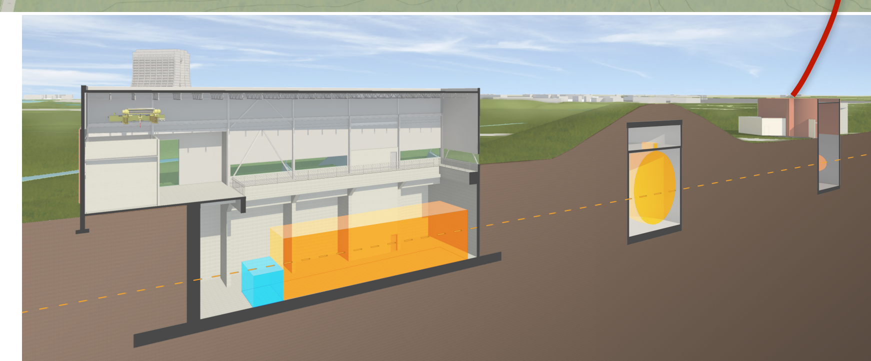

The MicroBooNE detector, which is currently in the final stages of installation, located in the Liquid Argon Test Facility (LArTF) at 470 m from the BNB target

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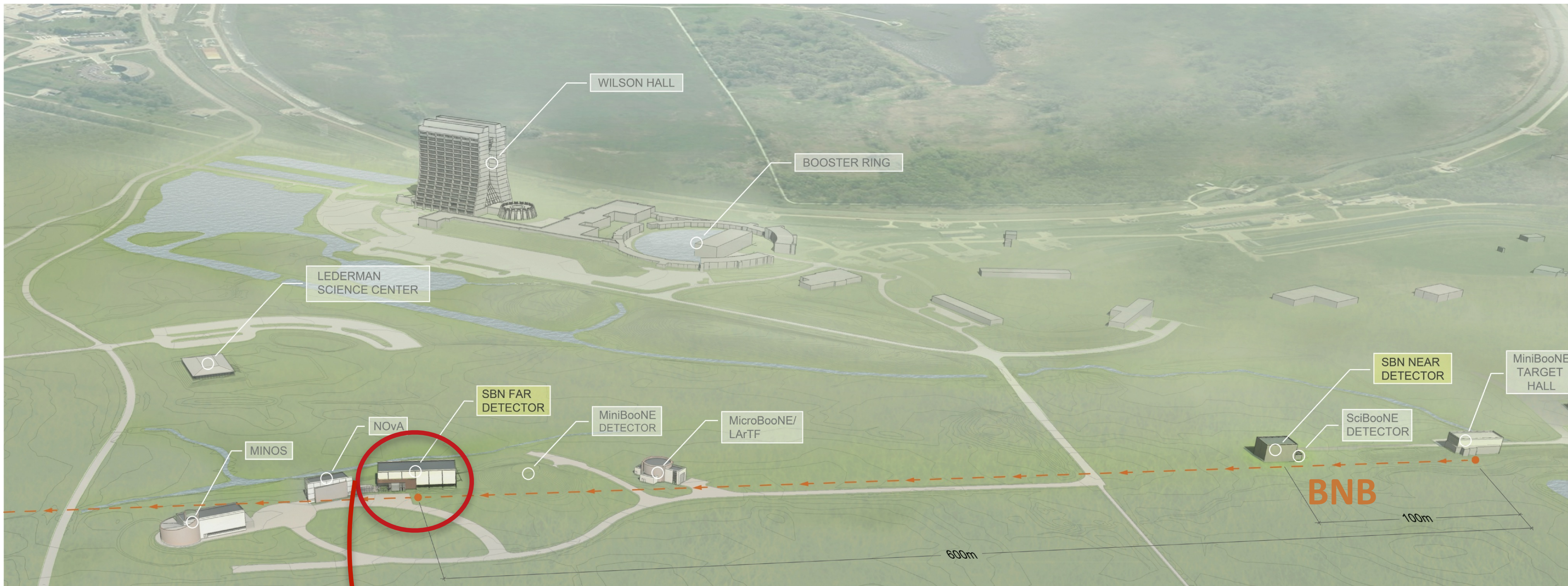

The far detector (ICARUS T600) will be located in a new building 600 m from the target between MiniBooNE and the NOvA near detector surface building

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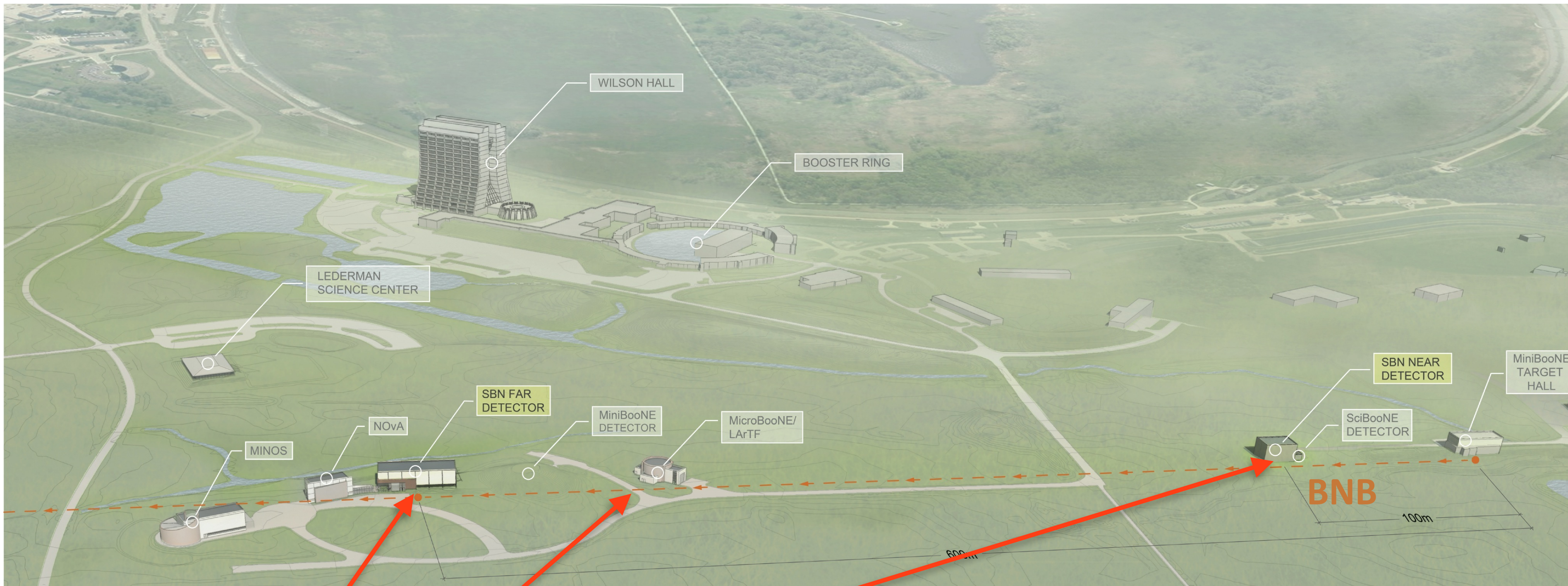


Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS T600	600 m	760 t	476 t

MicroBooNE

December 20th, 2013

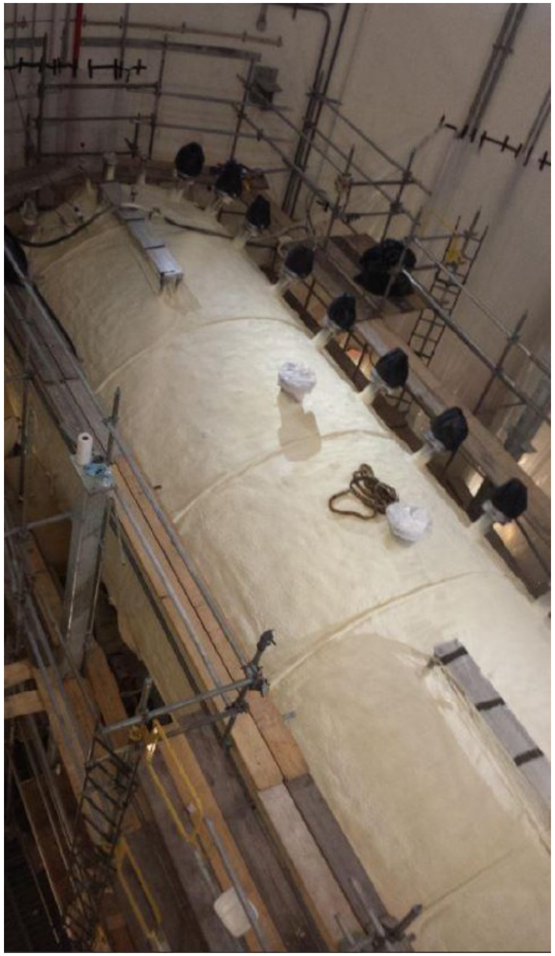
TPC dimensions:
10.3 m long x 2.3 m tall x 2.5 m wide
Active volume: 89 t of LAr

- 3 planes of wires with 3 mm wire spacing
- Drift distance: 2.5 m
- UV laser-based Electric Field calibration system
- PMT based Light collection system for the detection of scintillation light

Completed Detector moved to LArTF this summer

MicroBooNE

Final Installation underway, Commissioning has begun, LAr fill scheduled for January

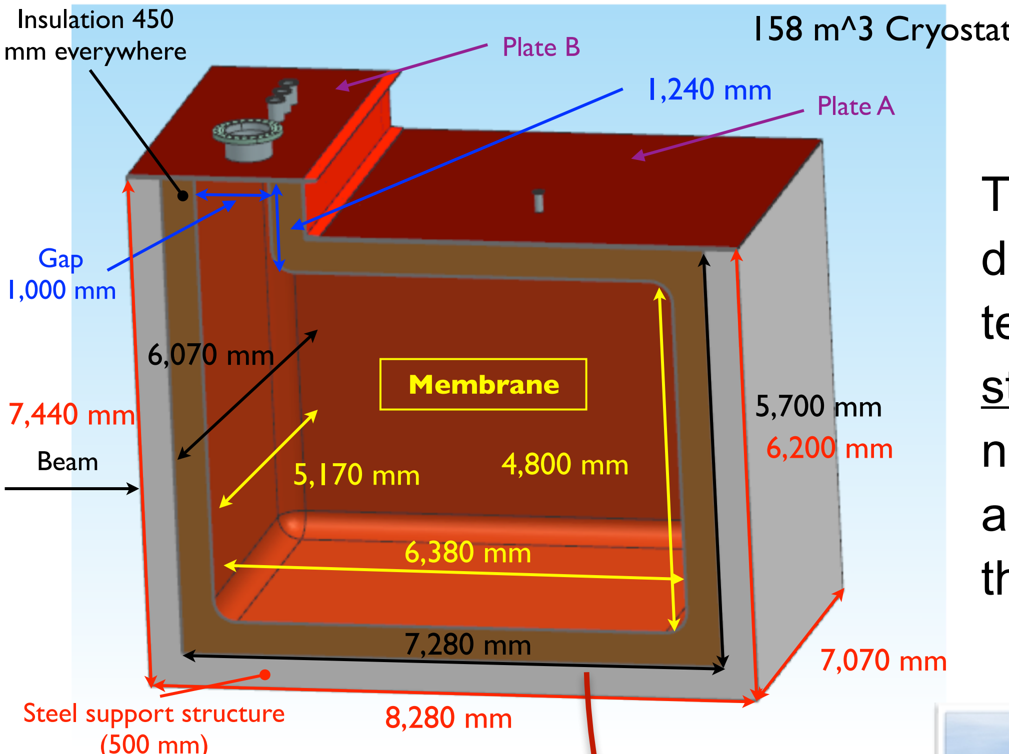


Detector insulated, in place in LArTF

6.2 km of cable installed in the month of September

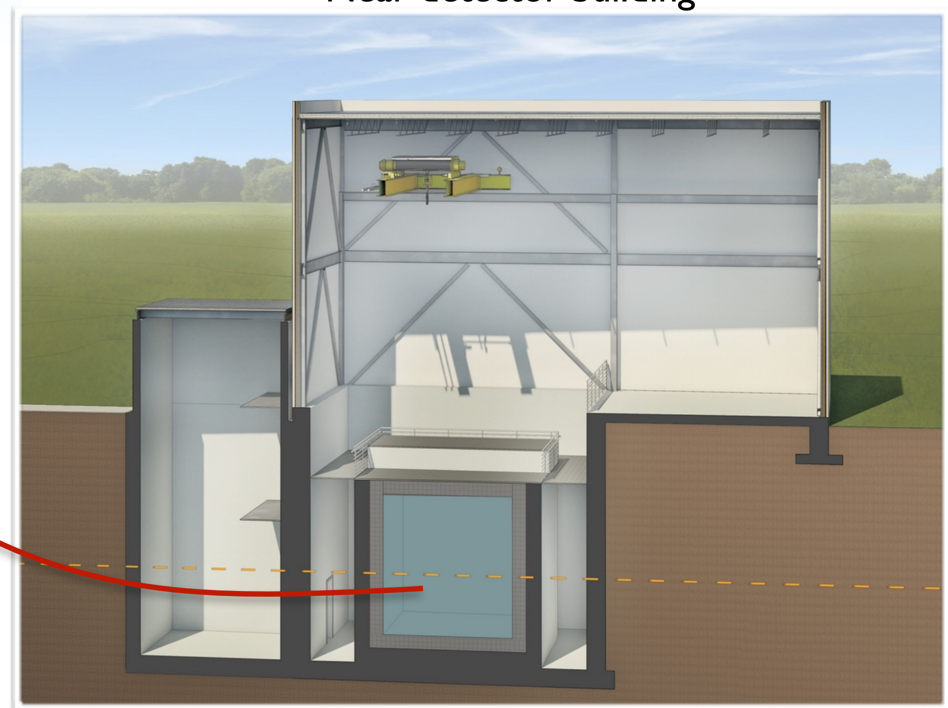
Electronics racks being installed in October

LAr1-ND



The basic concept of the LAr1–ND detector, based on LBNF-type technology, is to construct a <u>membrane-style cryostat</u> at 110 m from the Booster neutrino source in a new enclosure adjacent to and directly downstream of the existing SciBooNE hall.

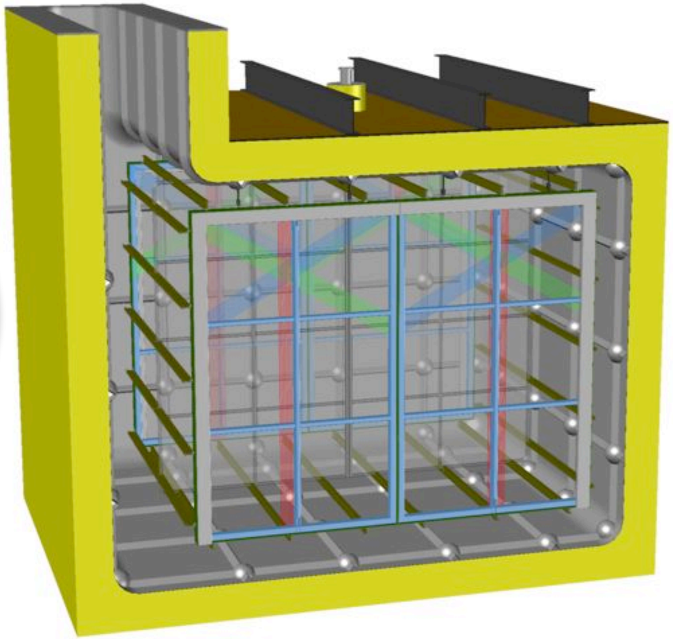
Near detector building

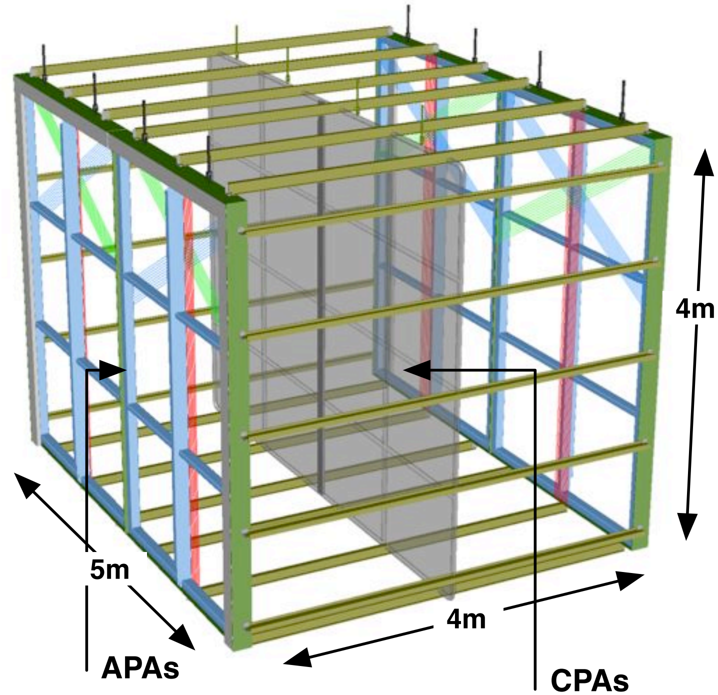


The membrane cryostat will house multiple CPAs (Cathode Plane Assembly) and APAs (Anode Plane Assemblies) to read out ionization electron signals.

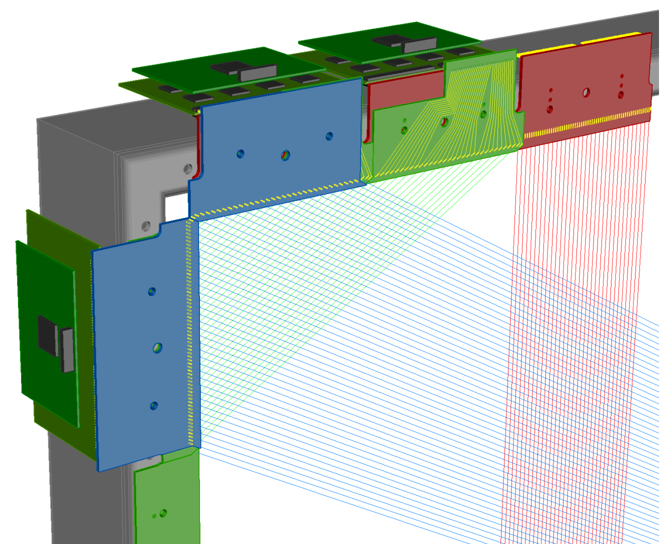
LAr1-ND

TPC dimensions:
4 m long x 4 m tall
x 5 m wide
Active volume:
112 t of LAr

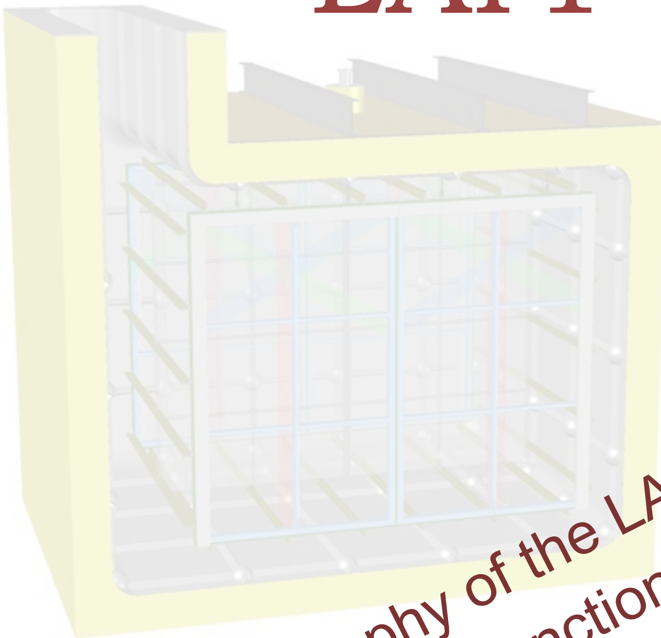




- The 4 APAs hold 3 planes of wires with 3 mm wire spacing each
- Drift distance: 2 m
- Wire readout arrangement identical to MicroBooNE (banks of cold electronics boards at the top and one vertical sides of each APA)
- UV laser-based calibration system
- Light collection system for the detection of scintillation light
- External cosmic ray tagging system



LAr1-ND



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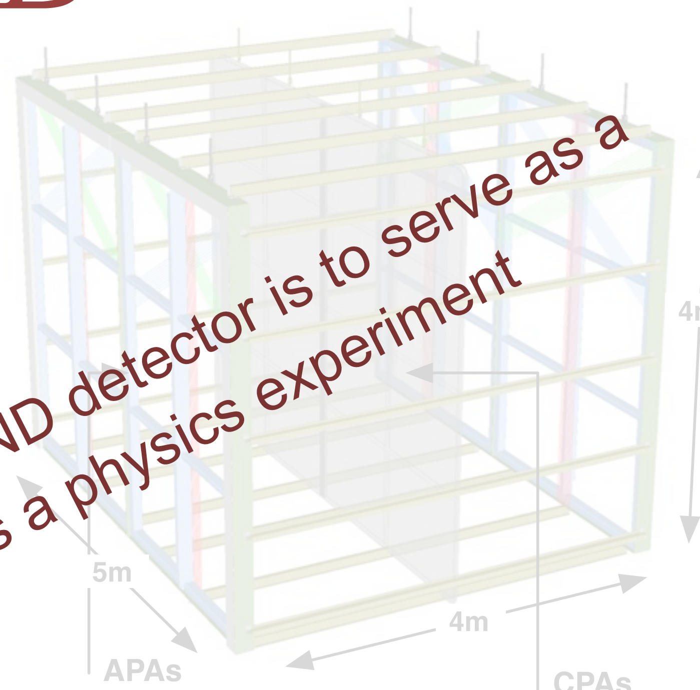


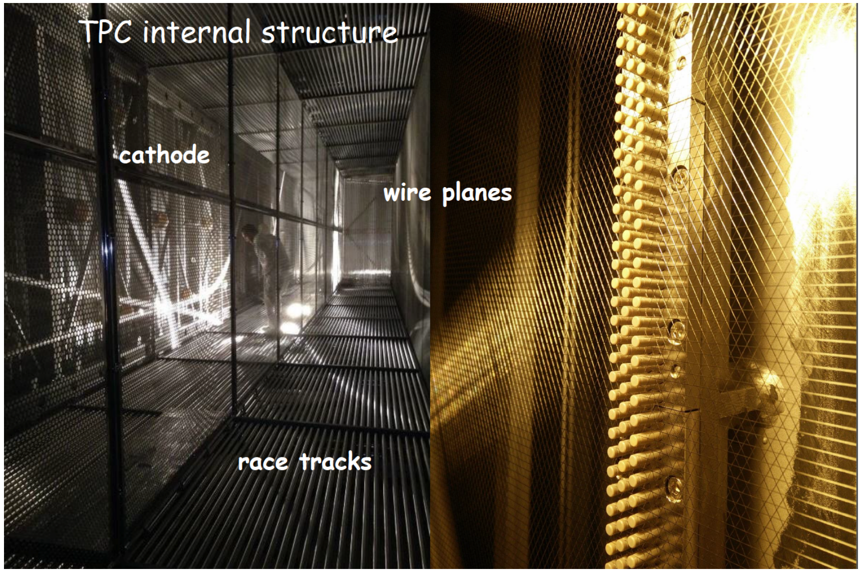
Overall, the design philosophy of the LAr1-ND detector is to serve as a prototype for LBNF that functions as a physics experiment

- The APAs hold ______ wire spacing
- Drift distance: ___
- Wire readout arrangement identical to MicroBooNE (banks of cold electronics boards at the top and one vertical sides of each APA
- UV laser-based calibration system
- Light collection system for the detection of scintillation light
- External cosmic ray

ICARUS T600

- The ICARUS T600 LAr-TPC has run smoothly and successfully for three years at LNGS, exposed to cosmic rays and the CNGS beam.
- The detector is now decommissioned, and a new project, WA104, is being carried on at CERN: it foresees the transport of the TPCs to CERN for a two-year overhauling procedure. This will prepare the detector to be deployed at Fermilab, as part of the forthcoming FNAL Short/Long Baseline neutrino programs.
- At CERN, the following main operations will be carried out on the TPCs:
  - Substitution of current cathode;
  - Substitution of current electronics with a more recent solution;
  - Upgrade of the light collection system, with new and more numerous devices;
  - Procurement of new cold vessels and insulation.
- In parallel, design and construction of a new 4π detector array surrounding the detector, to tag cosmic rays

ICARUS T600



- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs

- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0,±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light detection:
  - VUV sensitive (128nm) with wave shifter (TPB)

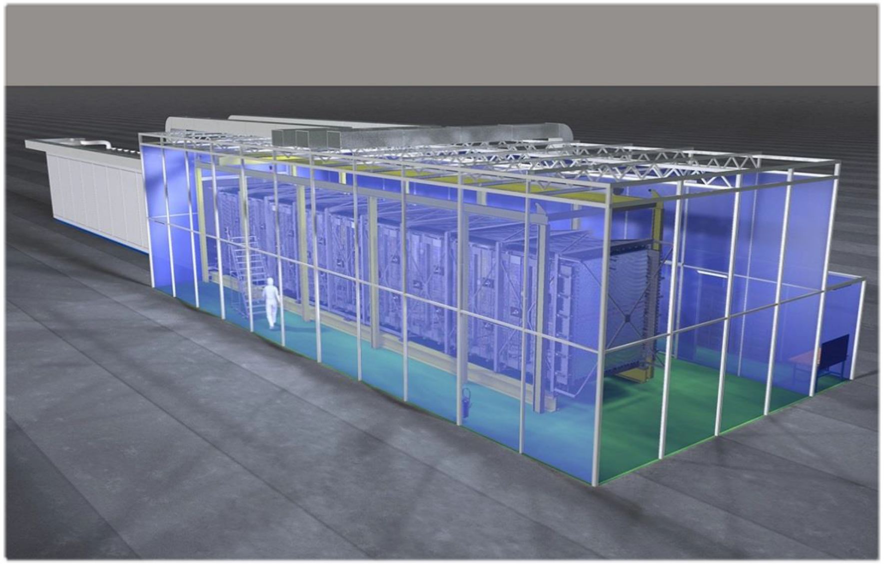
The first TPC arrived at CERN on Nov. 17

The second TPC will be transported ~ Dec. 10

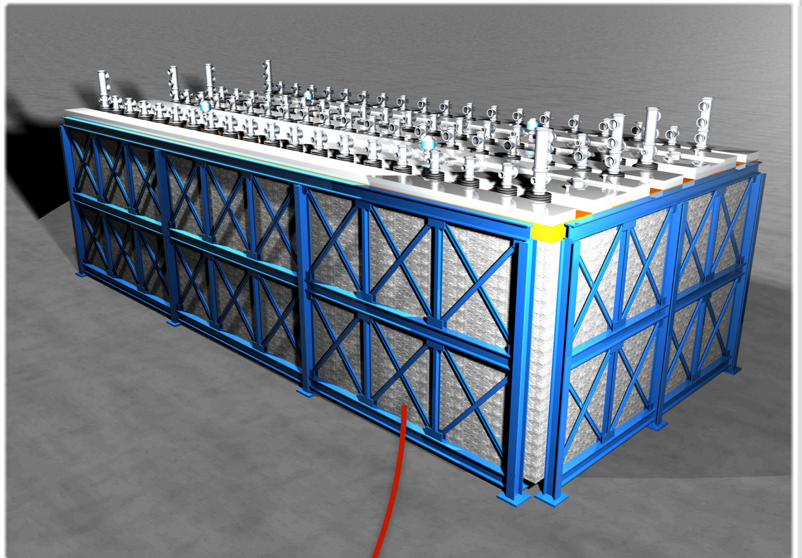
Transport from LNGS: vessel positioning in front of the TPC

ICARUS T600

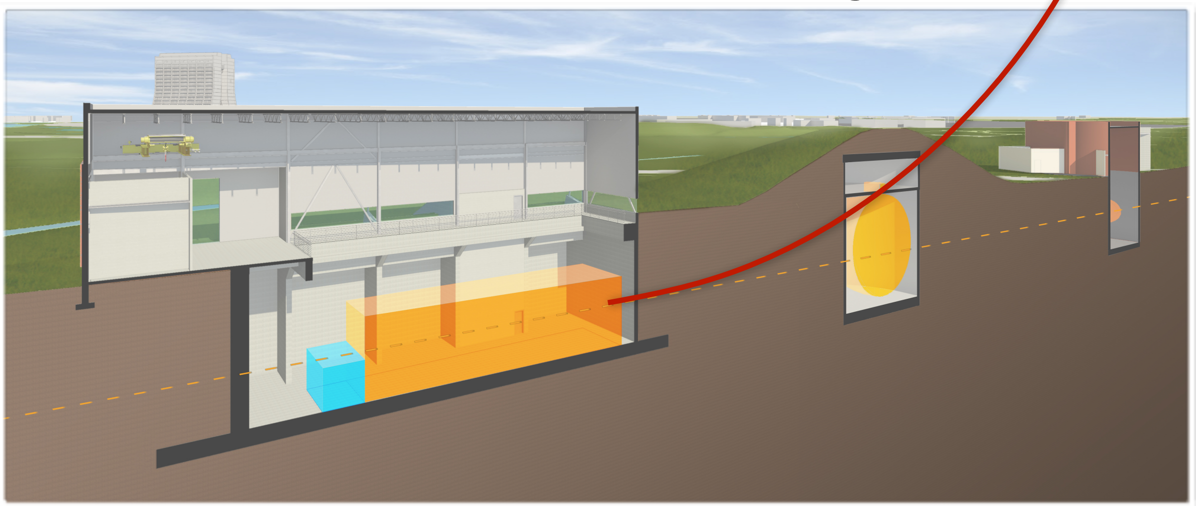
All overhauling activities will be carried on at CERN



New insulation and vessel



FNAL Far detector building



SBN - Physics Program

The SBN program of three LArTPC detectors along the Fermilab Booster Neutrino Beam delivers a rich and diverse physics opportunity:

- The source of the MiniBooNE excess will be directly checked in the same beam using the LArTPC technology in order to separate $e^{\pm}$ from single γ interactions

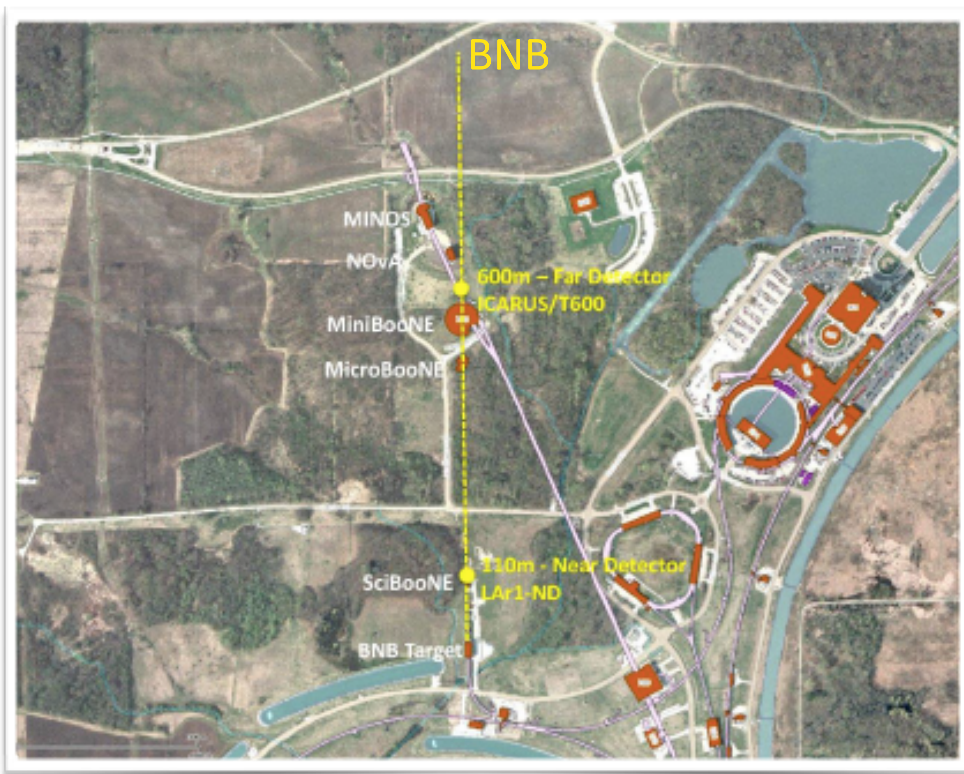
- **Multiple detectors** at different baselines allows a sensitive search for neutrino oscillations in multiple channels, i.e. $\nu_{\mu}\rightarrow\nu_{e}$ appearance and $\nu_{\mu}\rightarrow\nu_{x}$ disappearance

- Neutrino argon cross sections will be measured first in MicroBooNE and later in LAr1-ND using millions of interactions and the well characterized neutrino fluxes

- MicroBooNE and ICARUS T600 will also record samples of higher energy events, useful for LBNF, from the off-axis NuMI beam

SBN - Program schedule

- Goal set of having detectors ready for data taking in Spring 2018
- A time-effective program could allow LAr1-ND and ICARUS T600 to start the run at the end of the already approved MicroBooNE neutrino-mode run of 6.6×10^{20} POT

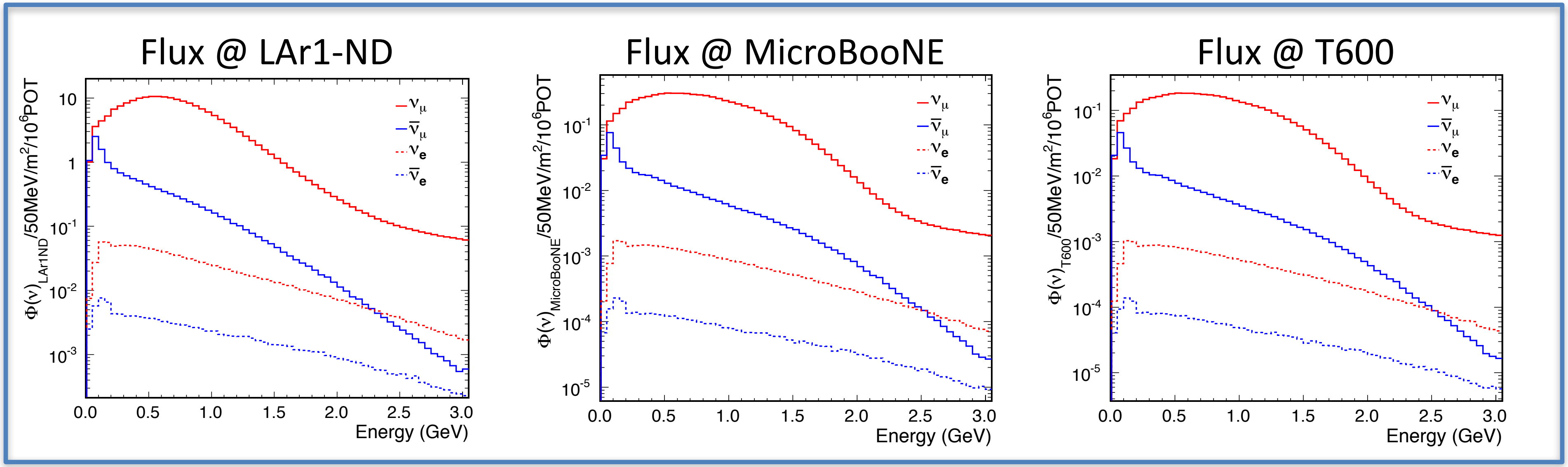


The Booster Neutrino Beam

- The Booster Neutrino Beam is created by extracting protons from the Booster accelerator at 8 GeV kinetic energy and impacting them on a 1.7 beryllium (Be) target to produce a secondary beam of hadrons, mainly pions.

- Charged secondaries are focused by a single toroidal aluminum alloy focusing horn that surrounds the target.

- The Booster spill length is 1.6 μs with nominally 5×10^{12} protons delivered to the beryllium target. The structure is a series of 81 bunches of protons each ~ 2 ns wide and 19 ns apart.

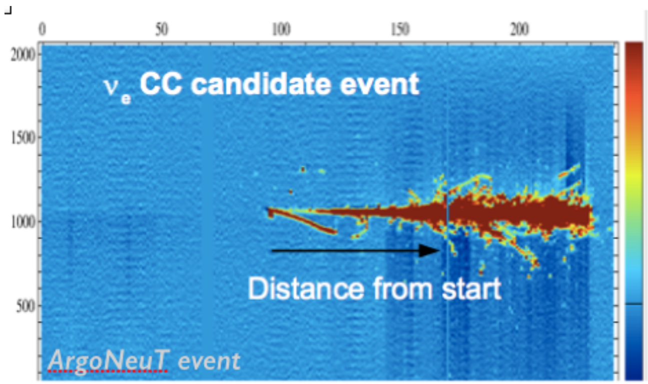


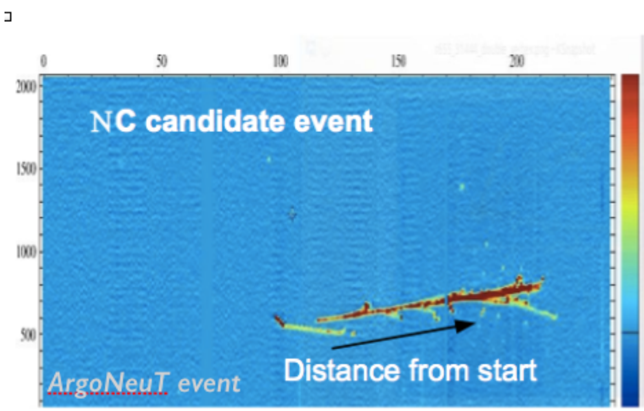
peak @ ~700 MeV, intrinsic ν_e rate ~5%

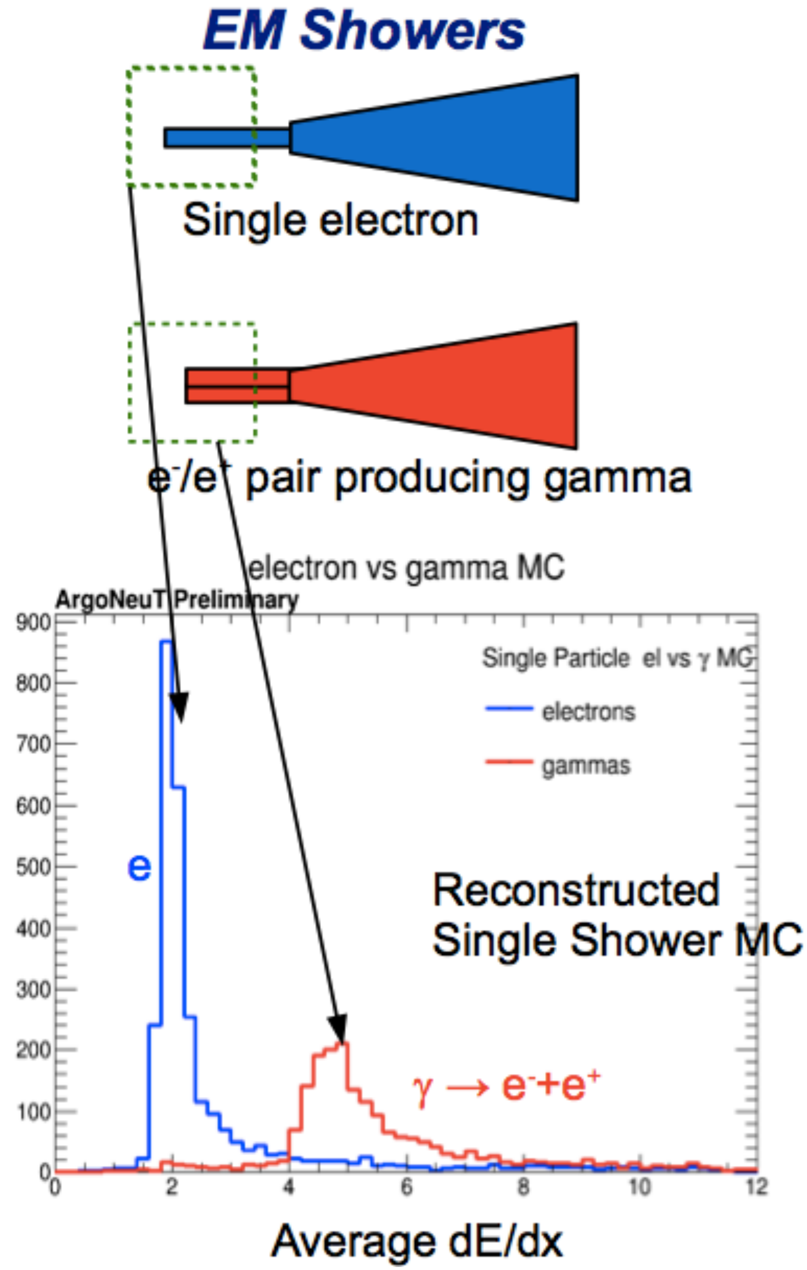
Electron-γ separation in LAr

- An EM shower that starts after a gap from the vertex is always background (especially if one can see two of them)

- Even if the gap is very small
  - in LAr can reconstruct the charge at the start of the shower - "dE/dx discrimination"





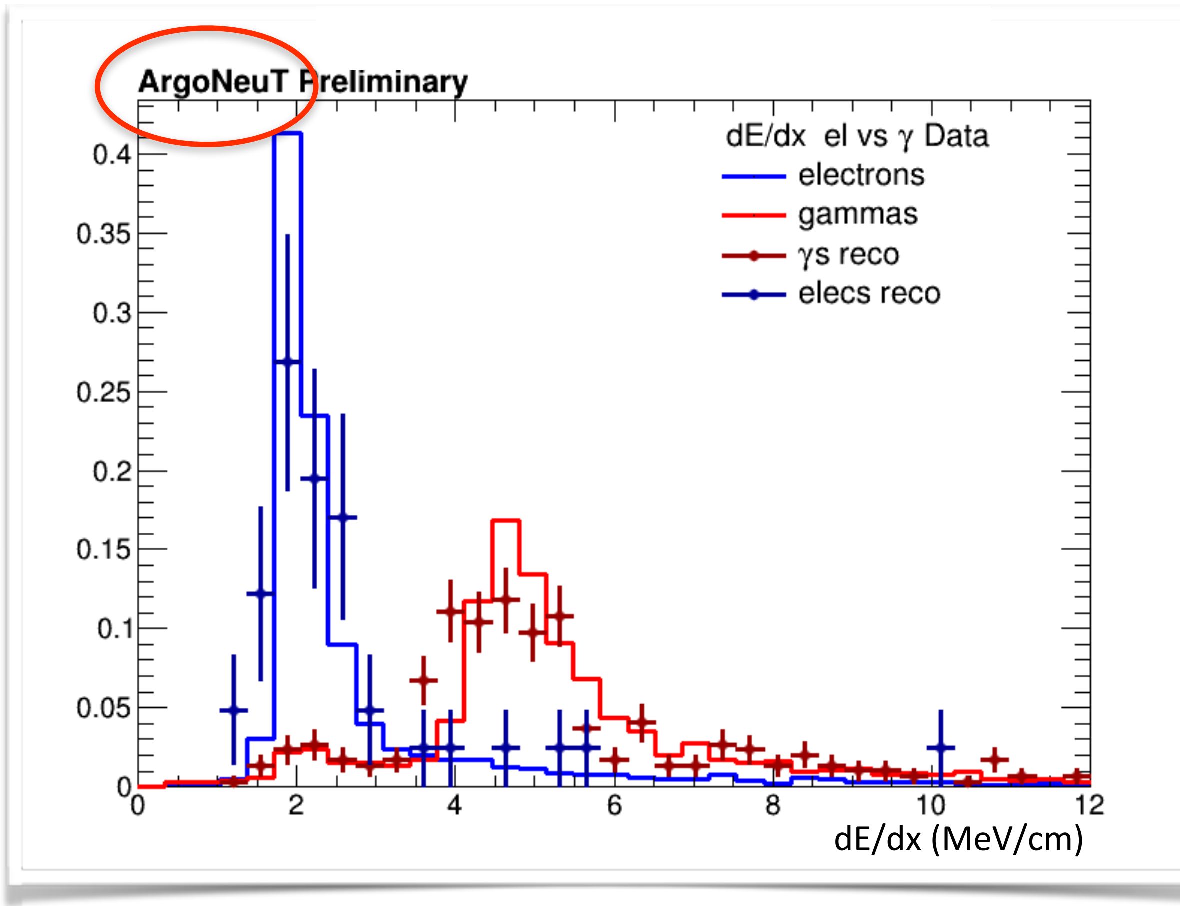


Electron-γ separation in LAr

dE/dx separation confirmed with data!

Gammas defined as EM showers detached from visible vertex

Electrons defined as EM showers with visible vertex and no gap



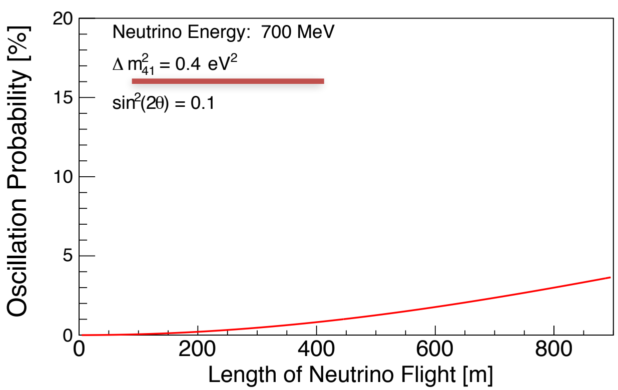
Physics Reach of the SBN FNAL Program: $\nu_\mu \rightarrow \nu_e$ Appearance and $\nu_\mu \rightarrow \nu_x$ Disappearance Sensitivities

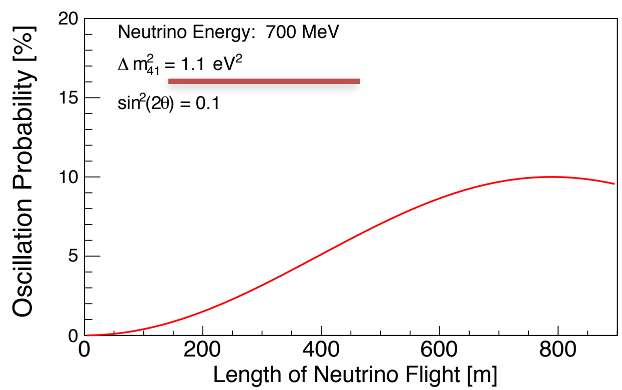
Analysis Method

- Assumed framework: three active and one sterile neutrino, a <u>"3+1 model"</u> as our baseline for sensitivity evaluation (a straight-forward way to compare to previous experimental results as well as to global data fits). Oscillation probabilities:

$$P^{3+1}_{\nu_\mu \to \nu_e} = \sin^2 2\theta_{\mu e} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \qquad P^{3+1}_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

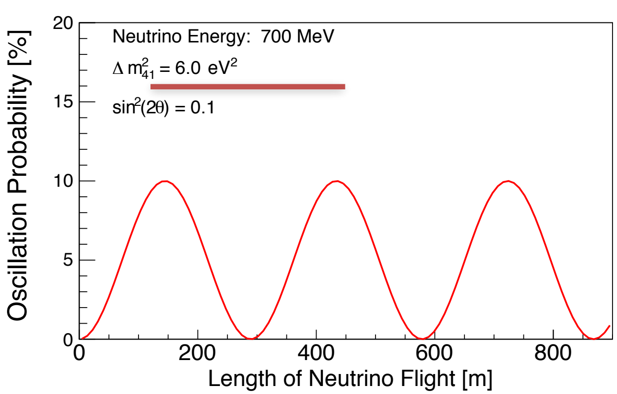
- Any observation of ν_e appearance due to oscillations must be accompanied by some amount of ν_μ disappearance as well.





For $\Delta m^2 < 1\ eV^2$:

- signal at the ND (110 m) is very small
- ND measurement is an excellent constraint on the intrinsic beam content.



For Δm^2 much larger than 1 eV^2:

- the oscillation wavelength becomes short compared to the 600 m baseline
- The oscillations are rapid and one observes an overall excess (or deficit) at all energies.
- Therefore the ND is also contaminated with signal and absolute normalization uncertainties become important in determining the sensitivity.

Analysis Method

- A full GEANT simulation in argon of GENIE produced neutrino interactions is used and selections are made based on Monte Carlo information in the event.

- The sensitivity is calculated by computing a χ^2 surface in the $(\Delta m^2_{41}, \sin^2 2\theta)$ oscillation parameter plane according to:

$$\chi^2(\Delta m^2_{41}, \sin^2 2\theta) = \sum_{i,j} \left[N_i^{null} - N_i^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right] (E_{ij})^{-1} \left[N_j^{null} - N_j^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right]$$

N_i^{null} = expected event distribution in the absence of oscillations

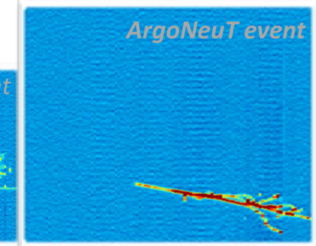
$N_i^{osc}(\Delta m^2_{41}, \sin^2 2\theta)$ = event prediction for an oscillation signal with $\sin^2 2\theta$ and Δm^2_{41}

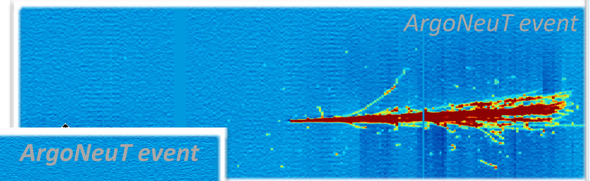
Statistical and systematic uncertainties are encoded in the covariance matrix E_{ij}.

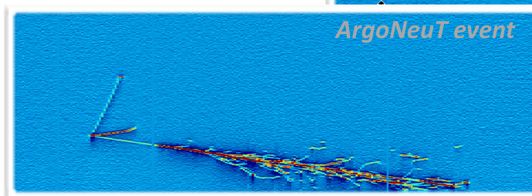
The labels *i* and *j* indicate bins of reconstructed neutrino energy

Electron Neutrino Charged-Current Candidates

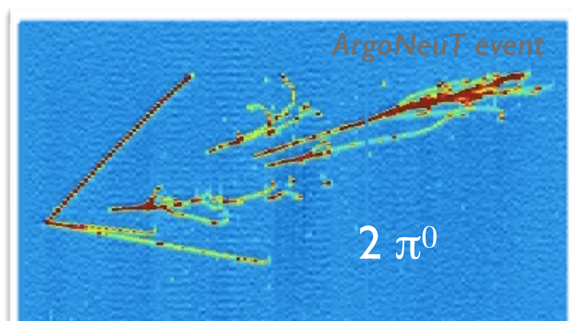
- Electron neutrino charged-current events are selected assuming 80% identification efficiency







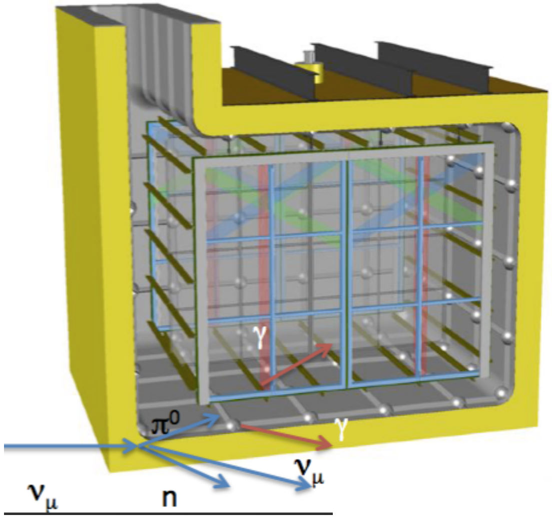
- Background events include:
  - Intrinsic ν_e CC events
  - Neutrino Electron Scattering events (the ν+e cross section is very low - secondary background)
  - NC π^0 production events with only one photon converting in the fiducial volume and no hadronic activity at the vertex. A 94% rejection efficiency from dE/dx cut is assumed
  - NC γ production events with the photon converting in the fiducial volume and no hadronic activity at the vertex. A 94% rejection efficiency from dE/dx cut is assumed
  - ν_μ CC events with a primary electromagnetic shower within the fiducial volume that could be misidentified as ν_e interactions if the muon is not identified. Careful hand-scans of simulated events have indicated this rate is <0.1%. The upper limit of 0.1% as a mis-ID rate is used
  - "Dirt" events (see next)
  - Cosmogenic events (see next)



Beam-Induced "Dirt" Events

- Neutrinos from the BNB will interact in the earth and other material surrounding the experiments (including dead argon outside of the TPC, the cryostat steel, structural elements or engineering support equipment in the detector hall, and the building walls and floors)

- These interactions can produce photons (through π^0 decay or other channels) which can enter the TPCs and convert in the fiducial volume, potentially faking an electron signal if one of the photon is undetected.



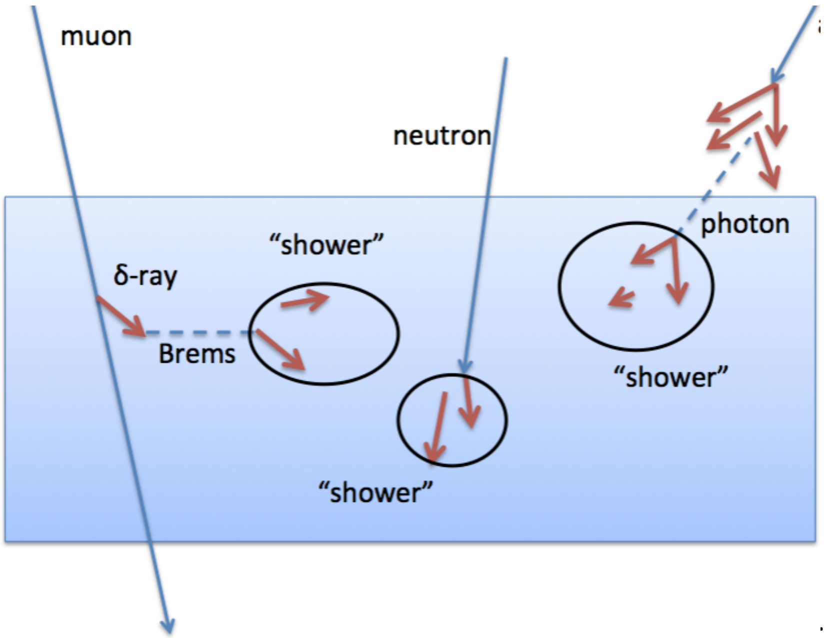
- To estimate this background, a Monte Carlo simulation is used which includes a realistic geometry description of the material surrounding the detectors:
  - The majority of the interactions producing this background occur relatively close to the detector volume (within a few 10's of centimeters of the TPC boundary)
  - The conversion point within the active volume of these externally produced photons is near the TPC boundary. Dirt background events can be reduced by a 30 cm active buffer upstream of the fiducial volume in each detector.

Cosmogenic Backgrounds

- Given the shallow depth location of the detectors, an important background to consider are cosmogenic events. Cosmogenic photons (mostly produced by bremsstrahlung of delta-rays produced by cosmic muons) that generate electrons in the detector via Compton scattering or via pair production that mimic a ν_e- like interaction signature are potentially background to ν_e appearance.

- All background events falling within the acquisition time, which corresponds to the maximum electron drift time (1.28 ms in LAr1-ND, 1.6 ms in MicroBooNE and 0.96 ms in ICARUS), may have influence on the data analysis. If the timing information is known for every track or shower inside the detector, only cosmogenic events in coincidence with the beam spill (1.6 sec duration) are background.

- Several independent determinations of the cosmic flux were evaluated at the shallow depth using simulations with the CRY or FLUKA cosmic-ray shower simulation as a primary particle generator.
  Cosmogenic particles were then propagated around and inside the detectors with GEANT4 or FLUKA.



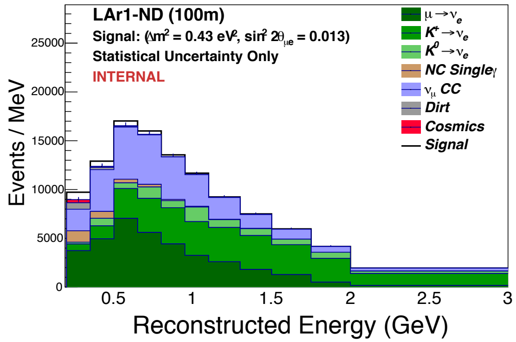
Cosmogenic Backgrounds

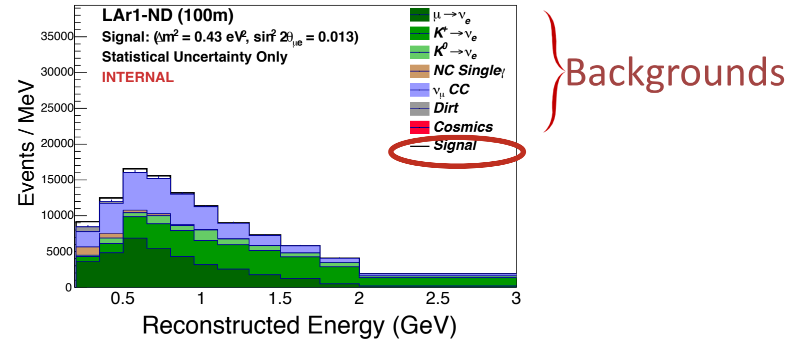
- An energy threshold of 200 MeV (used in the oscillation analysis) largely reduce this background

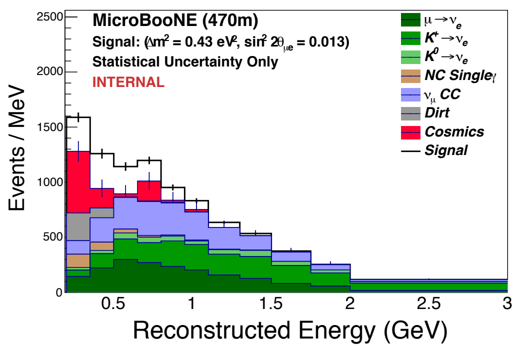
- A number of different strategies can be applied to further reduce it:
  - Most of the pair production events with just one photon detected can be rejected with the reconstruction of dE/dx in the initial part of the shower.
  - Distance of the photon conversion point from the parent muon track, whenever it also crosses the detector. A cylindrical “muon anti-fiducial volume” of 15 cm radius cuts 98% of the background electrons.
  - Scintillation light detection system capable to associate different light pulses with different event segments would allow a drastic reduction of backgrounds. Optimization of the light detection systems is progressing for all detectors.
  - A muon tagging system external to the fiducial volume with position and timing information would greatly facilitate the reconstruction and identification of muon tracks.

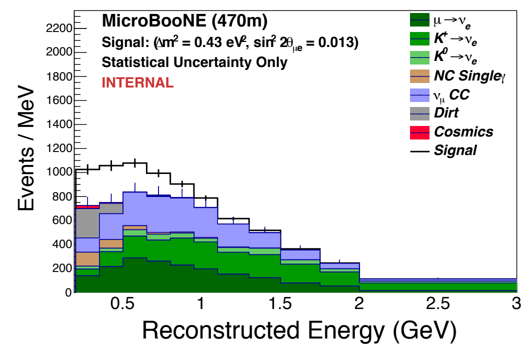
ν_e CC Candidate

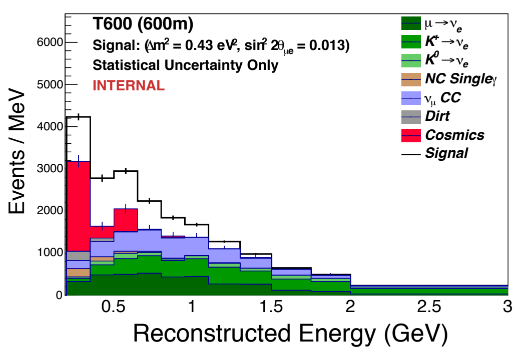
LAr1-ND (6.6×10^{20} POT)
MicroBooNE (1.3×10^{21} POT) and T600 (6.6×10^{20} POT)

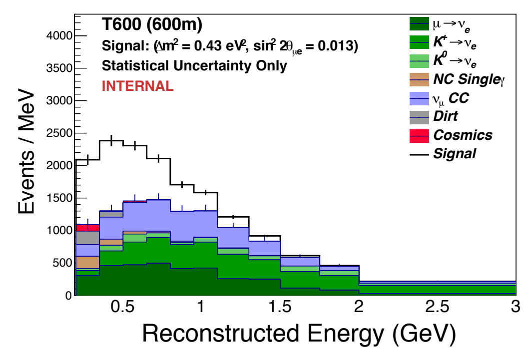










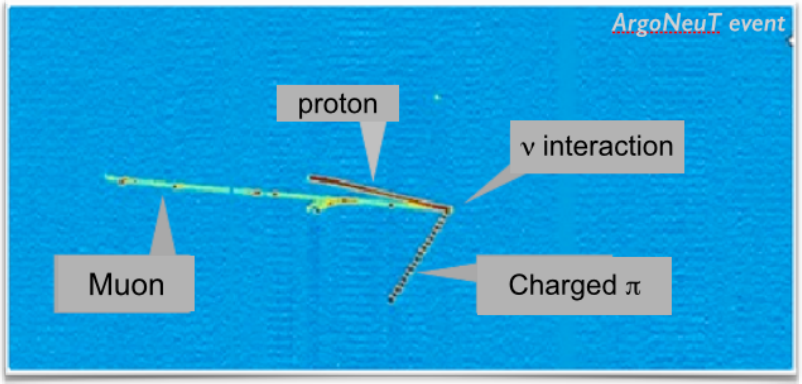


Proximity to muon and dE/dx cuts used to reject cosmogenic background sources

A combination of the internal light collection systems and external cosmic tagger systems at each detector are used to identify 95% of the triggers with a cosmic muon in the beam spill time and those events are rejected.

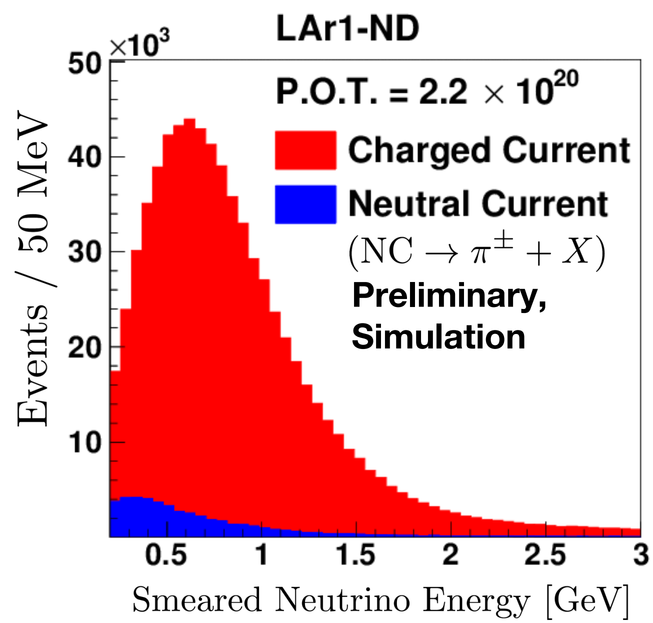
Muon Neutrino Charged-Current Candidates

- Muon neutrino charged-current events are selected assuming an 80% efficiency



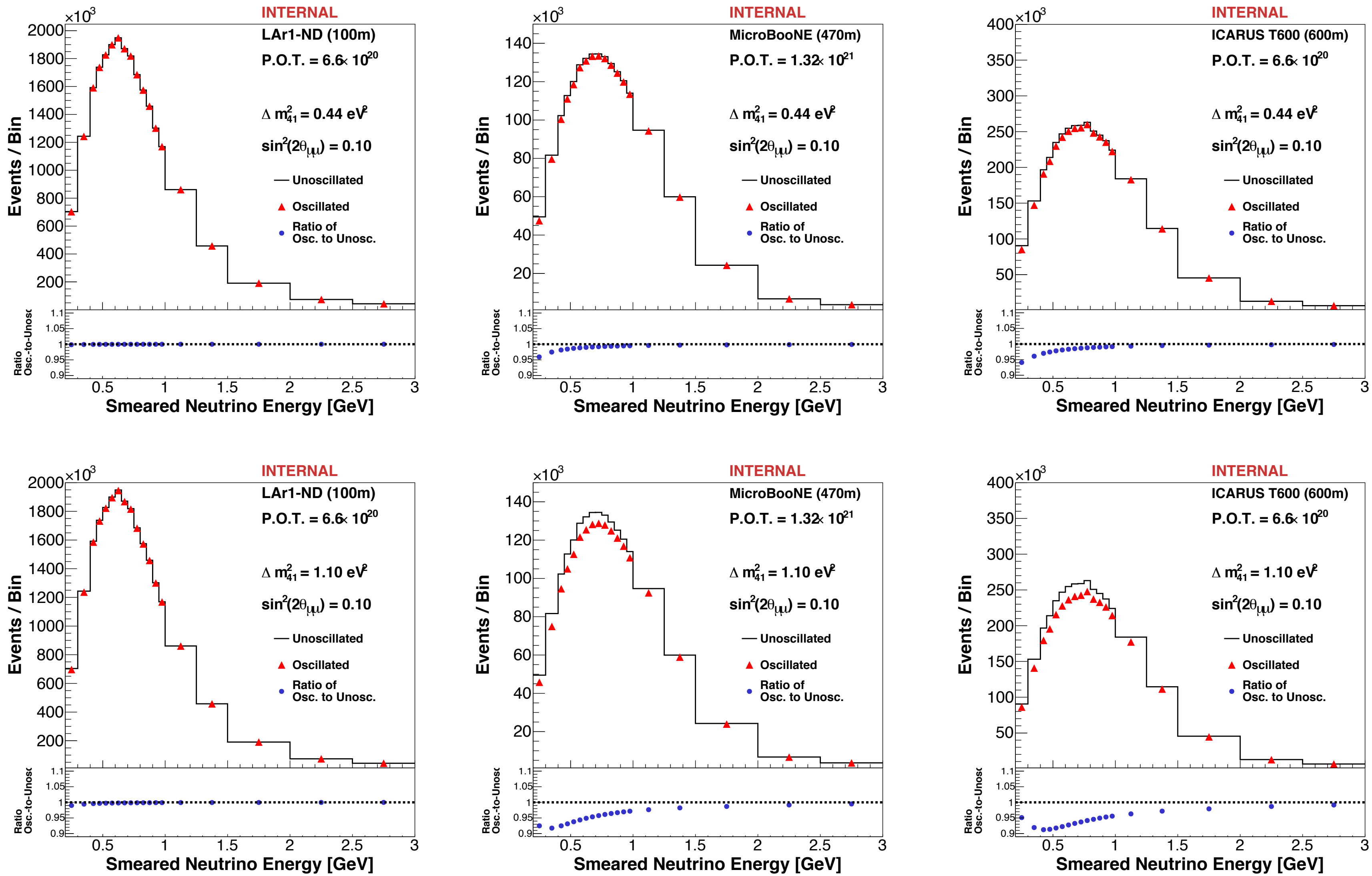
- The ν_μ rate is not affected by dirt or cosmogenic backgrounds

- The major background contribution coming from neutral charged pion production has been found to be small with a negligible impact on the oscillation sensitivity



ν_μ CC rates

Examples of disappearance signals in the SBN detectors



Analysis Method

- A full GEANT simulation in argon of GENIE produced neutrino interactions is used and selections are made based on Monte Carlo information in the event.

- The sensitivity is calculated by computing a χ^2 surface in the $(\Delta m^2_{41}, \sin^2 2\theta)$ oscillation parameter plane according to:

$$\chi^2(\Delta m^2_{41}, \sin^2 2\theta) = \sum_{i,j} \left[N_i^{null} - N_i^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right] (E_{ij})^{-1} \left[N_j^{null} - N_j^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right]$$

N_i^{null} = expected event distribution in the absence of oscillations

$N_i^{osc}(\Delta m^2_{41}, \sin^2 2\theta)$ = event prediction for an oscillation signal with $\sin^2 2\theta$ and Δm^2_{41}

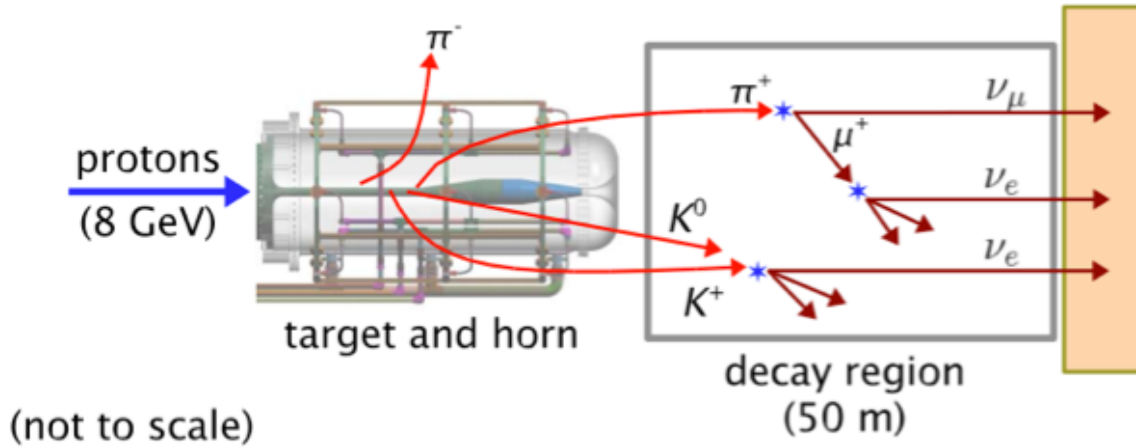
Statistical and systematic uncertainties are encoded in the covariance matrix E_{ij}.

The labels *i* and *j* indicate bins of reconstructed neutrino energy

- The total systematic covariance matrix is a combination of independent matrices constructed for each of the systematic uncertainties considered:

$$E^{\text{syst}} = E^{\text{flux}} + E^{\text{cross section}} + E^{\text{cosmic bkgd}} + E^{\text{dirt bkgd}} + E^{\text{detector}}$$

Neutrino Flux Uncertainties



- BNB is an extensively studied neutrino flux and constrained by data (A.A. Aguilar-Arevalo et al., PRD 79, 072002 (2009))

- Same simulation as MiniBooNE to estimate the variations in hadron production, horn current, off target production, …the BNB Monte Carlo treats systematic uncertainties related to the following sources:

  - Primary production of π^+, π^-, K^+, K^-, and K^0_L in p+Be collisions at 8 GeV
  - Secondary interactions of p, n, $\pi^\pm$ in the beryllium target and aluminum horn
  - Beam focusing with the magnetic horn

Neutrino Cross Section Uncertainties

Simulation performed using the GENIE event generator. Cross section uncertainties are quantified within the framework of event reweighing that GENIE provides

Parameter	Description	Nominal %
M_A^{CCQE}	Axial mass for CC quasi-elastic	-15%+25%
M_A^{CCRES}	Axial mass for CC resonance neutrino production	±20%
M_A^{NCRES}	Axial mass for NC resonance neutrino production	±20%
$R_{bkg}^{\nu p,CC1\pi}$	Non-resonance background in $\nu p, CC$ 1π reactions.	±50%
$R_{bkg}^{\nu p,CC2\pi}$	Non-resonance background in $\nu p, CC$ 2π reactions.	±50%
$R_{bkg}^{\nu n,CC1\pi}$	Non-resonance background in $\nu n, CC$ 1π reactions.	±50%
$R_{bkg}^{\nu n,CC2\pi}$	Non-resonance background in $\nu n, CC$ 2π reactions.	±50%
$R_{bkg}^{\nu p,NC1\pi}$	Non-resonance background in $\nu p, NC$ 1π reactions.	±50%
$R_{bkg}^{\nu p,NC2\pi}$	Non-resonance background in $\nu p, NC$ 2π reactions.	±50%
$R_{bkg}^{\nu n,NC1\pi}$	Non-resonance background in $\nu n, NC$ 1π reactions.	±50%
$R_{bkg}^{\nu n,NC2\pi}$	Non-resonance background in $\nu n, NC$ 2π reactions.	±50%
$DIS - NuclMod$	DIS Nuclear Modification	
NC	Neutral Current	

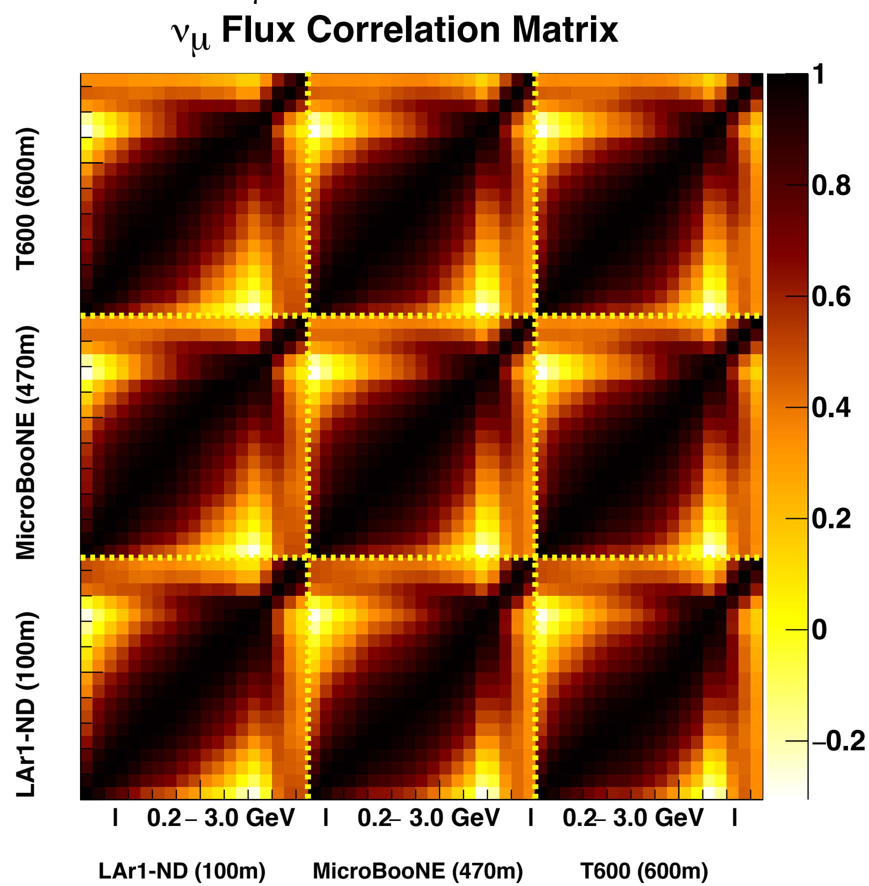
Systematic Uncertainties

Flux and Neutrino Cross Section uncertainties E^{flux} , $E^{cross\ section}$:

- Absolute - Total normalization uncertainties are of order 10-15% on both absolute ν_e and ν_μ fluxes and cross sections

- Correlated - the fluctuations due to flux and cross section uncertainties are highly correlated between the three detectors for both ν_e and ν_μ.

The high statistics measurement made in the near detector, together with the high levels of correlations between the near and far locations will eliminate the large normalization uncertainties when performing oscillation searches. This is a critical motivation for the multi-detector SBN configuration



Systematic Uncertainties

Dirt background Uncertainties $E^{\text{dirt bkg.}}$:

- The error matrix associated with the dirt backgrounds: we conservatively estimate a 15% systematic uncertainty uncorrelated between detectors, but fully correlated within each detectors energy spectrum

Using ν_e candidate events very near the TPC boundary we can select a sample which is enhanced in dirt background events and use it to validate the simulations.

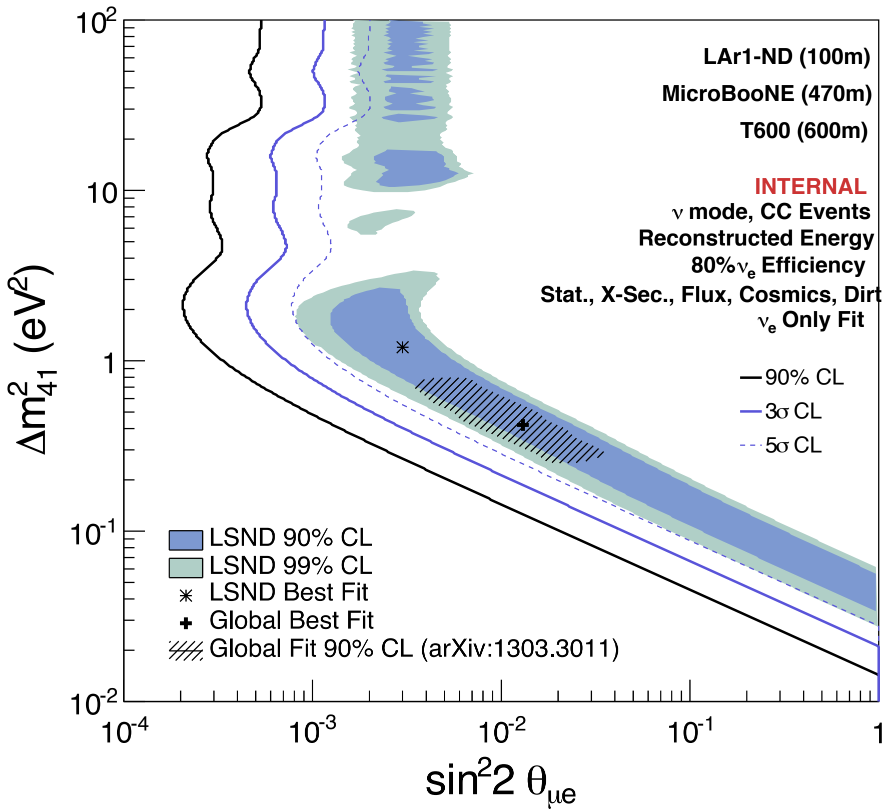
Cosmic background Uncertainties $E^{\text{cosmic bkg.}}$:

- We haven't included systematics for the cosmic bkg. It is assumed to be small compared to the other uncertainties because we will be able to measure the cosmic background and the selection efficiencies with random triggers in between spills or in beam-off periods.

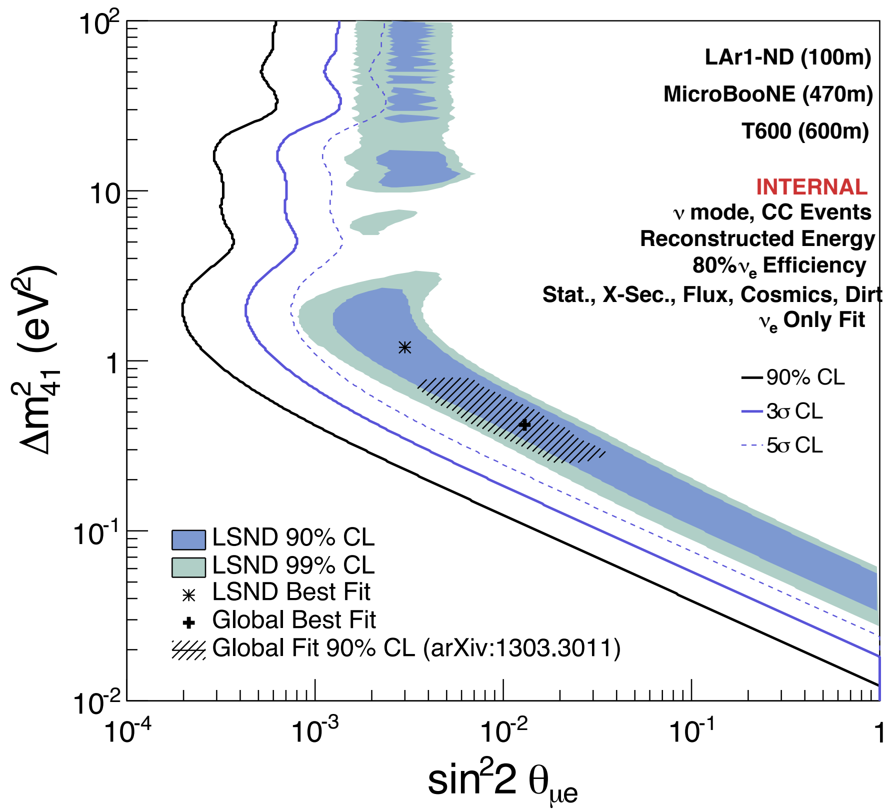
$\nu_\mu \rightarrow \nu_e$ Appearance Sensitivity

LAr1-ND (6.6×10^{20} POT)
MicroBooNE (1.3×10^{21} POT) and T600 (6.6×10^{20} POT)

Sensitivity predictions for the SBN program to $\nu_\mu \rightarrow \nu_e$ oscillations
including all backgrounds and systematic uncertainties



Proximity to muon and dE/dx cuts used to reject cosmogenic background sources



A combination of the internal light collection systems and external cosmic tagger systems at each detector are used to identify 95% of the triggers with a cosmic muon in the beam spill time and those events are rejected.

$\nu_\mu \rightarrow \nu_x$ Disappearance

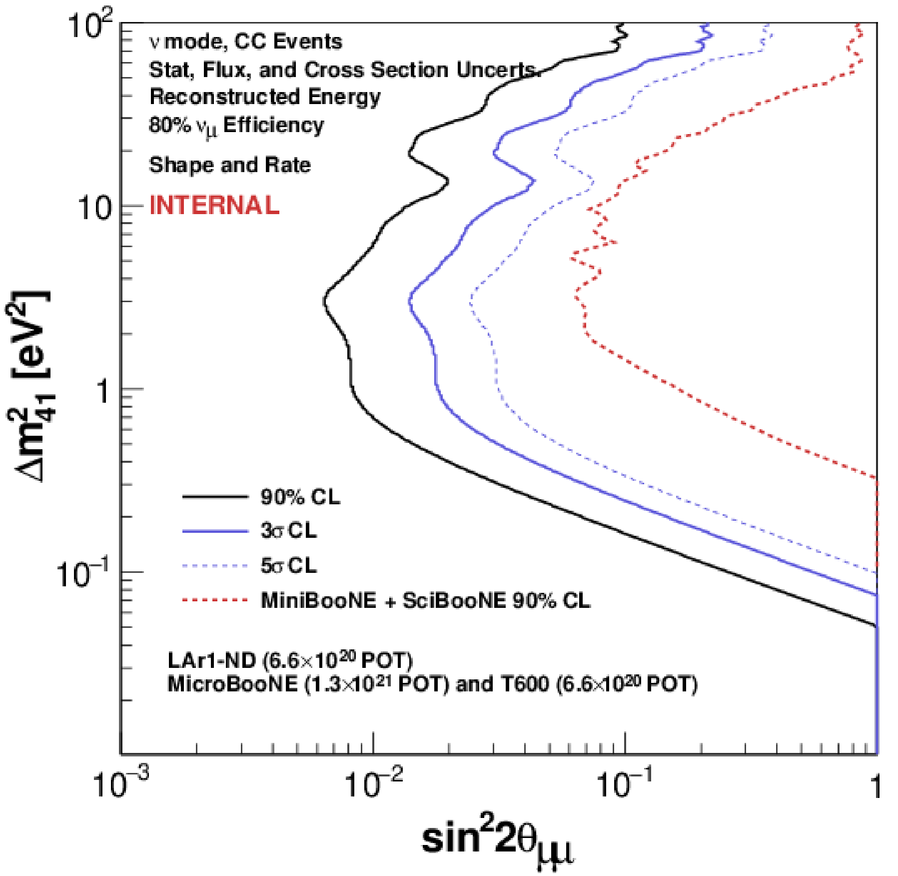
- The neutrino flux and interaction model uncertainties are important. The absolute flux and cross section uncertainties in any detector are >10%

- But the high correlations between the near detector and the MicroBooNE/T600 event samples along with the excellent statistical precision of the LAr1-ND measurements will make the SBN program the most sensitive disappearance experiment around Δm^2= 1 eV^2 ever performed

$\nu_\mu \rightarrow \nu_x$ Disappearance Sensitivity

Sensitivity predictions for the SBN program to $\nu_\mu \rightarrow \nu_x$ oscillations including systematic uncertainties

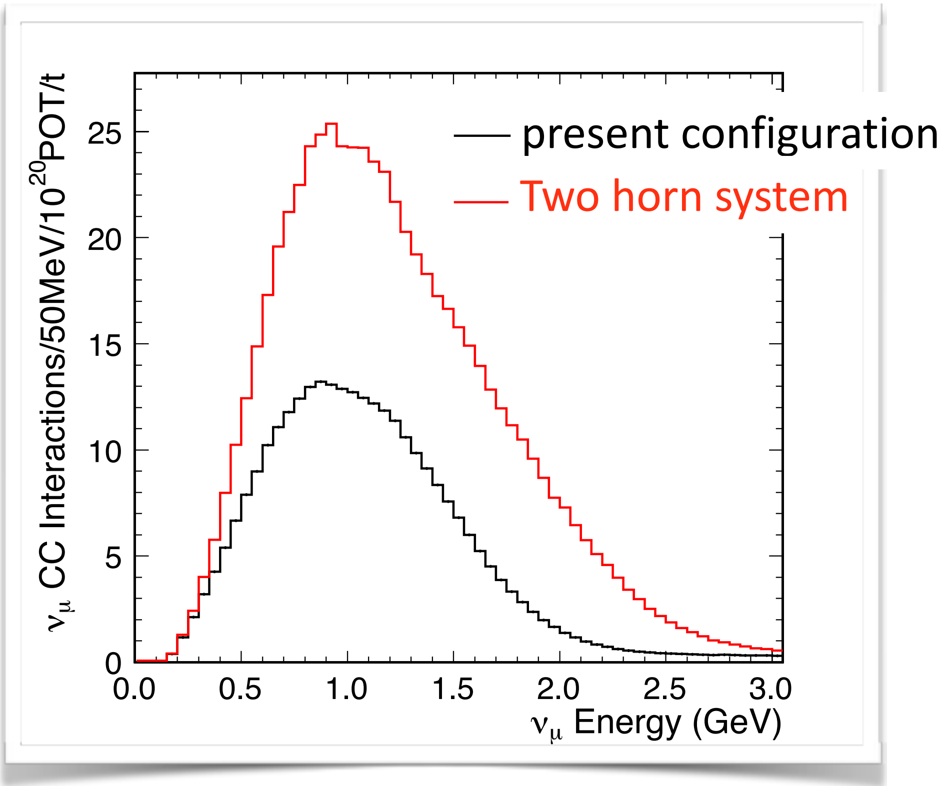
LAr1-ND (6.6×10^{20} POT)
MicroBooNE (1.3×10^{21} POT) and T600 (6.6×10^{20} POT)



SBN can extend the search for muon neutrino disappearance an order of magnitude beyond the SciBooNE-MiniBooNE combined analysis

BNB improvements

- The initial physics studies are all based on the assumption that no modifications will be made to the BNB target and horn.
- However, studies are on-going to determine what changes could be made to the target and horn to re-optimize for a program based on LArTPC detectors and increase event rates per proton on target along the BNB ➔ Optimized <u>two horn system</u>



Conclusions

- The future short-baseline neutrino program of three LAr TPs detectors builds upon the existing FNAL Booster Neutrino Beam and the MicroBooNE detector

  - There are important physics questions to be answered, and Fermilab can be the first to address them

  - A SBL program offers an ideal opportunity for continued development of the liquid argon TPC technology, combining timely neutrino physics measurements with vital experience in detector development for a community working toward LBNF

"A Proposal for a Future Short-Baseline Neutrino Oscillation Program on the Fermilab Booster Neutrino Beam" in preparation.
To be submitted to January 2015 PAC

Overflow

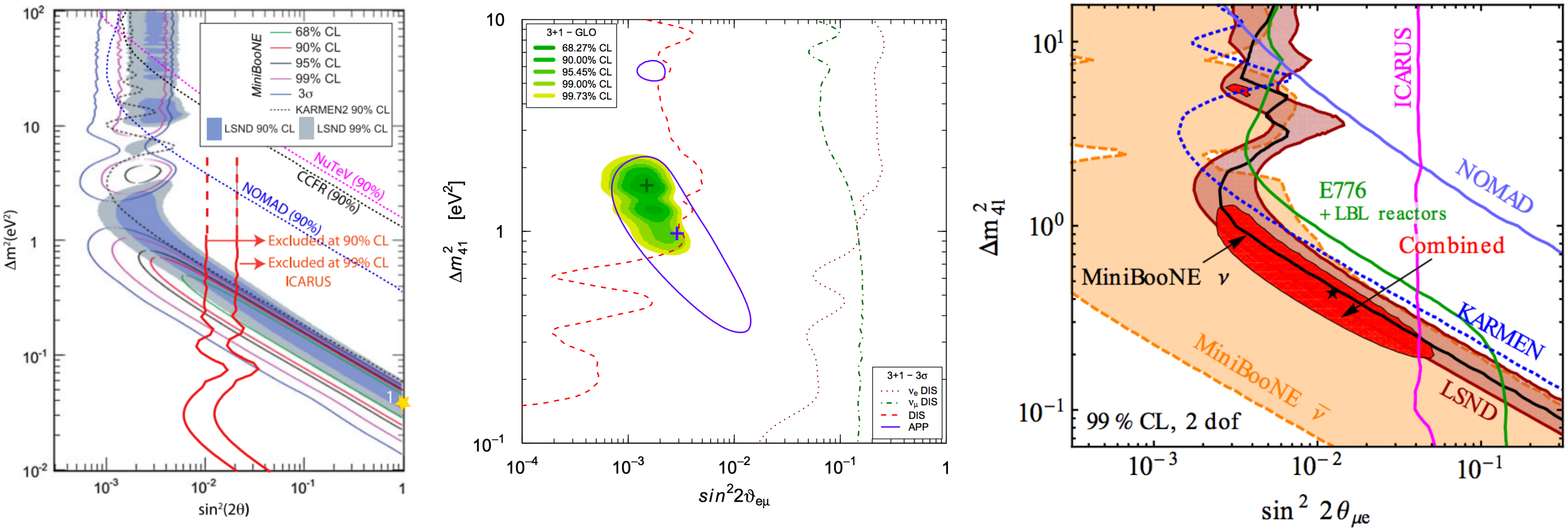


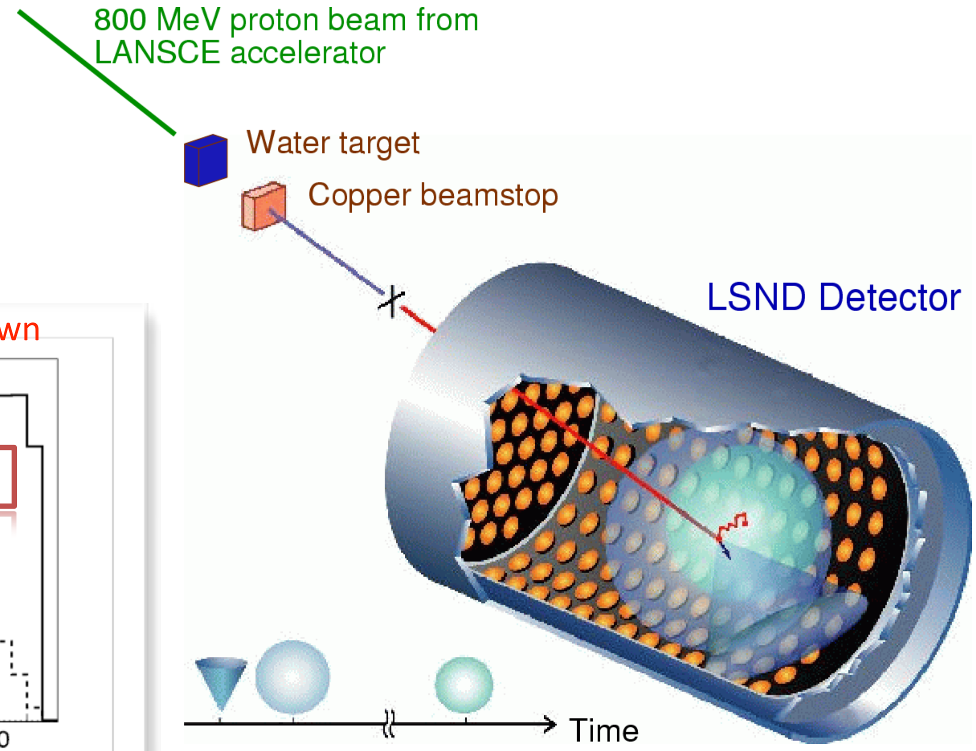
FIG. 8: *(Left) The main published experimental results sensitive to $\nu_\mu \to \nu_e$ in this Δm^2 range [15–18, 25–28] including the present ICARUS limit [24] from the run in Gran Sasso. Global data analysis of short-baseline neutrino experiment results from Giunti et al. [29] (center) and Kopp et al. [30] (right). The blue closed contour on the left and the red solid area on the right are the allowed parameter regions for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data and both indicate preferred Δm^2_{41} values in the $\sim$[0.2–2] eV^2 range.*

Liquid Scintillator Neutrino Detector (LSND)

1 $\pi^+ \rightarrow \mu^+ \nu_\mu$

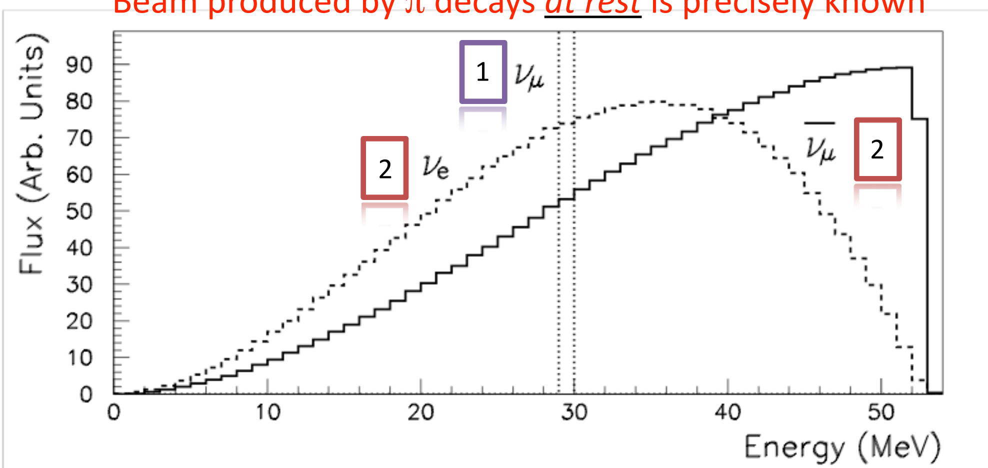
2 $\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

? $\hookrightarrow \bar{\nu}_e$



167 tons of mineral oil

Beam produced by π decays *at rest* is precisely known



Look for electron anti-neutrinos in a beam with well-predicted fluxes and small electron anti-neutrino background

neutron captures to produce a 2.2 MeV gamma

Baseline of 30 m
E= [20 – 50] MeV

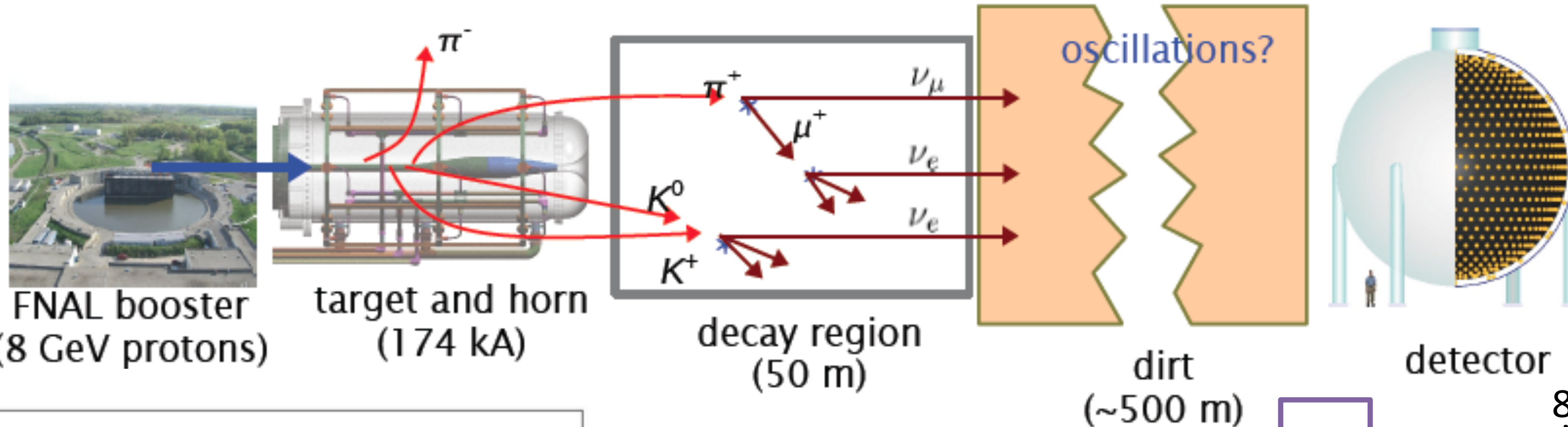
L/E ≈ 1 m / MeV

$\bar{\nu}_e$ detection via inverse-beta-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
(coincidence signal)

Phys. Rev. D64 (2001) 112007; hep-ex/0104049

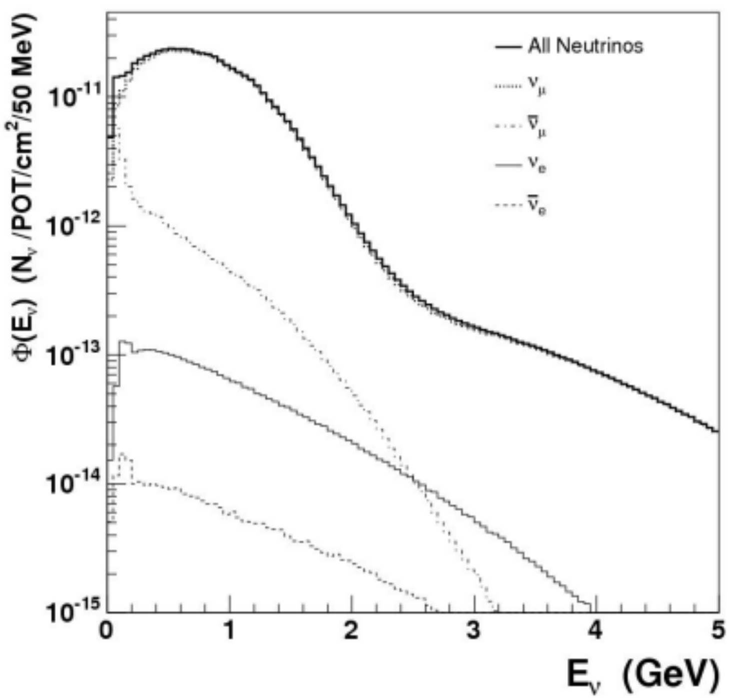
MiniBooNE

Designed to follow up on the LSND result as oscillations but with different ν source (π decay in flight), different detections, thus different systematics



800 t of mineral oil

$\boxed{L}$



$\boxed{E}$

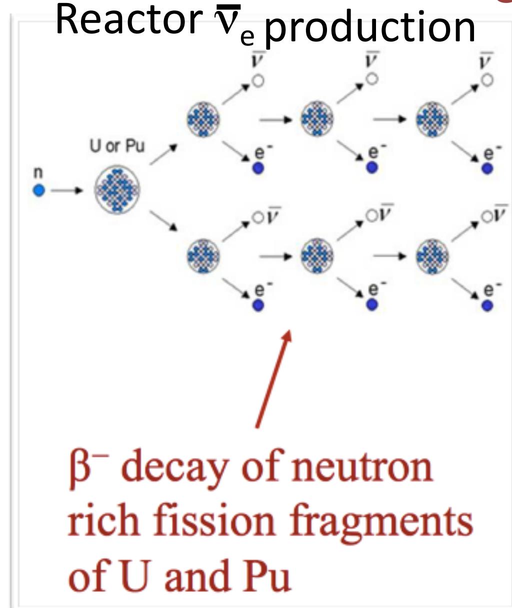
$$L/E \sim 1 \;\; \mathrm{m/MeV}$$

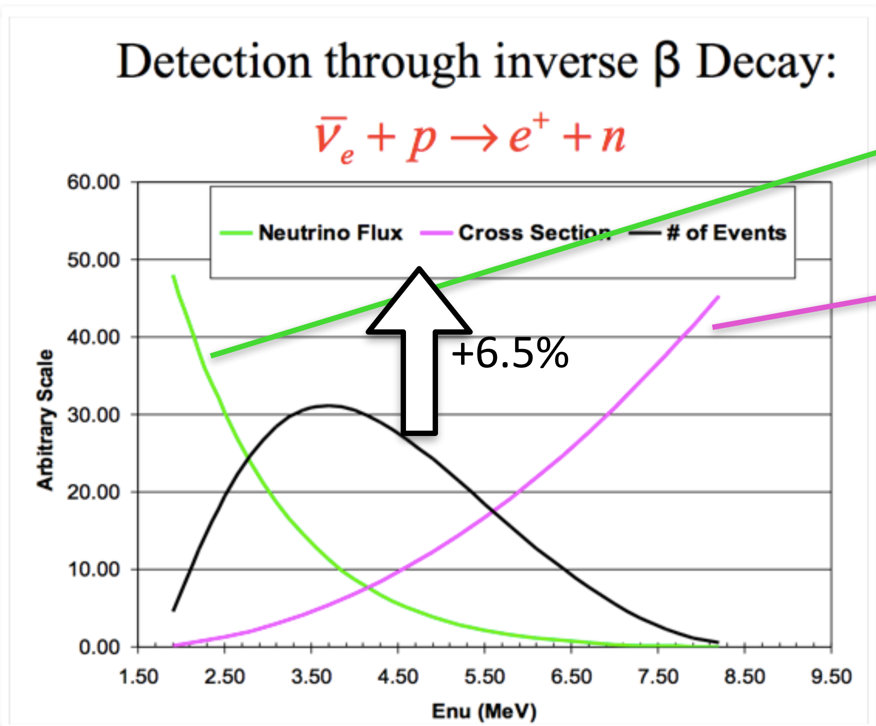
same as LSND

CC interaction in mineral oil

Reactor Antineutrino Anomaly

- In preparation for Double Chooz analysis with a single far detector improved procedure to go from measured β^- spectra to neutrino spectra
  Th. A. Mueller et al. Phys. Rev. C83 (2011) 054615; arXiv:1101.2663.
- Result was a net 3.5% increase in the estimated rates on average relative to previous predictions
  G. Mention et al. Phys. Rev. D83 (2011) 083006; arXiv:1101.2755.





Improved reactor neutrino spectra +3.5%*

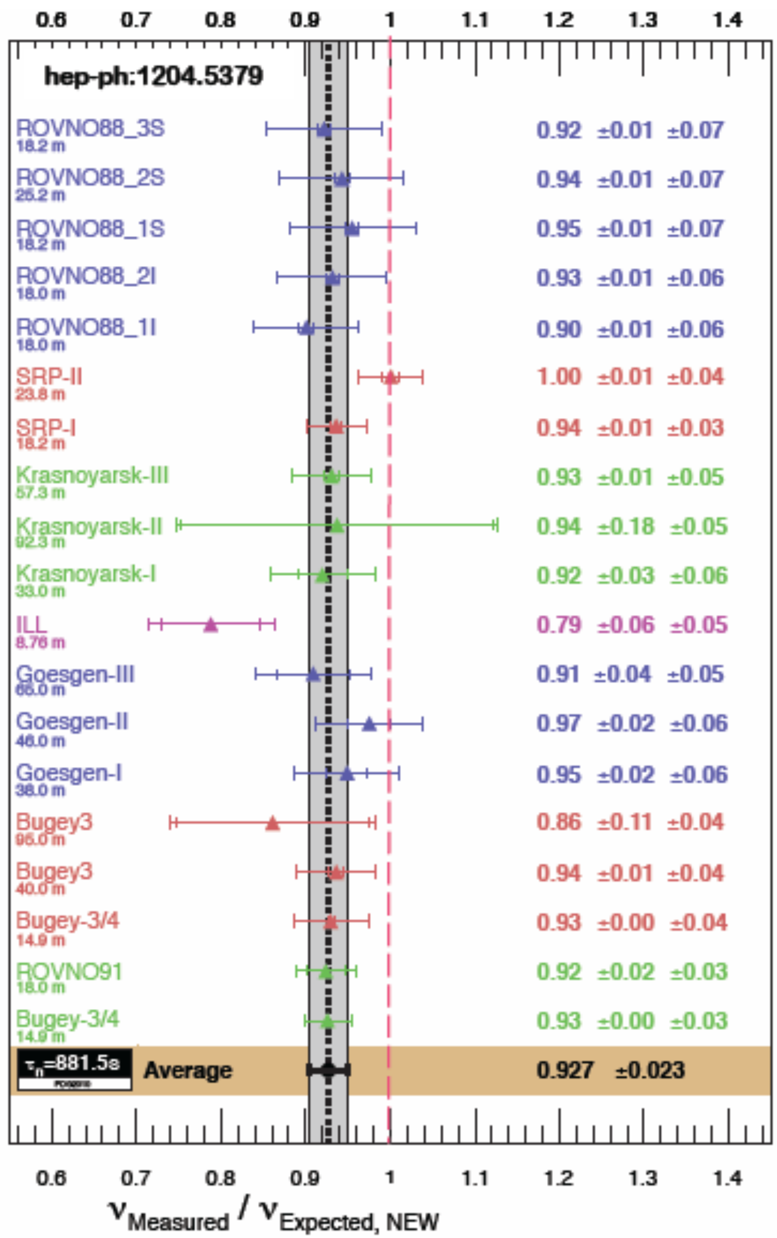
Accounting for long-lived isotopes in reactors → +1%

Reevaluation of σ_{IBD} → +1.5%

Led to reanalysis of all past SBL reactor experiment

* Recent calculation, using a different method, found a similar shift
P. Huber, arXiv:1106.0687.

Reactor Antineutrino Anomaly

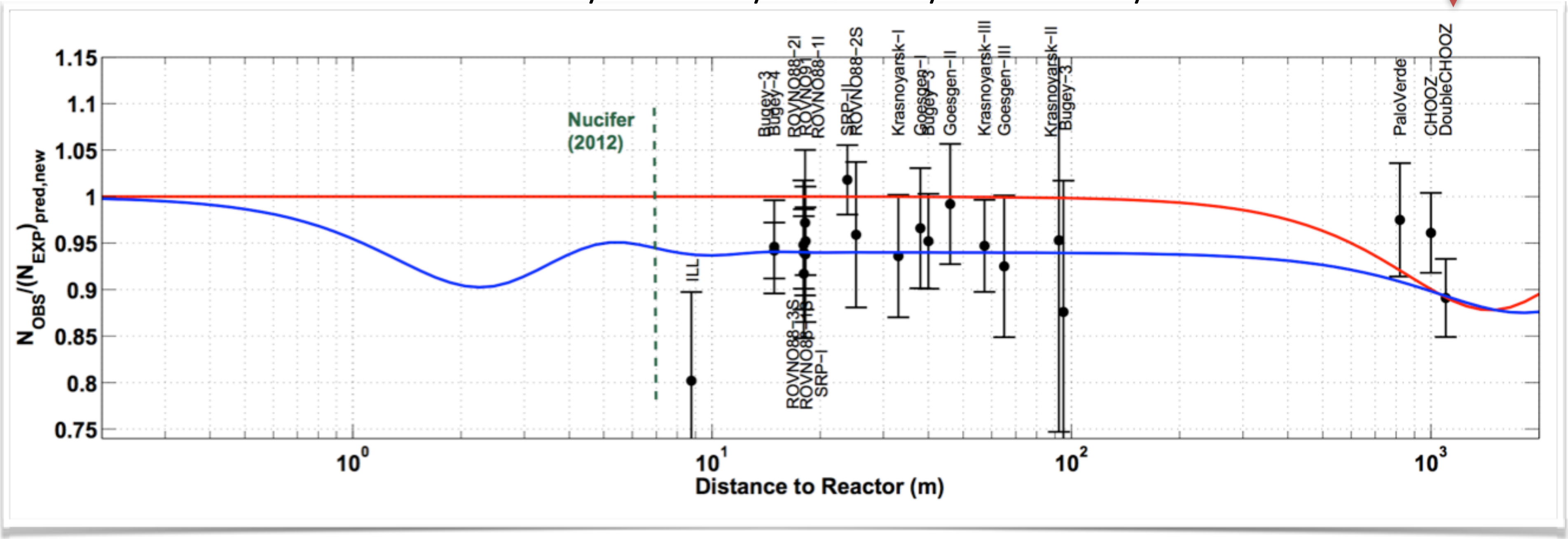


- 19 Short Baseline Experiments (L<100m)
- Observables: ratios of observed event rate to predicted rate of events
- 2011 results
  - Average: μ = 0.943 ± 0.023
  - 98.6 % C.L. deviation from μ = 1
- 2012 results
  - Average μ = 0.927 ± 0.023
  - 99.7 % C.L. deviation from μ = 1
- 2013: update: refined analysis

Reactor Antineutrino Anomaly

atmospheric L/E

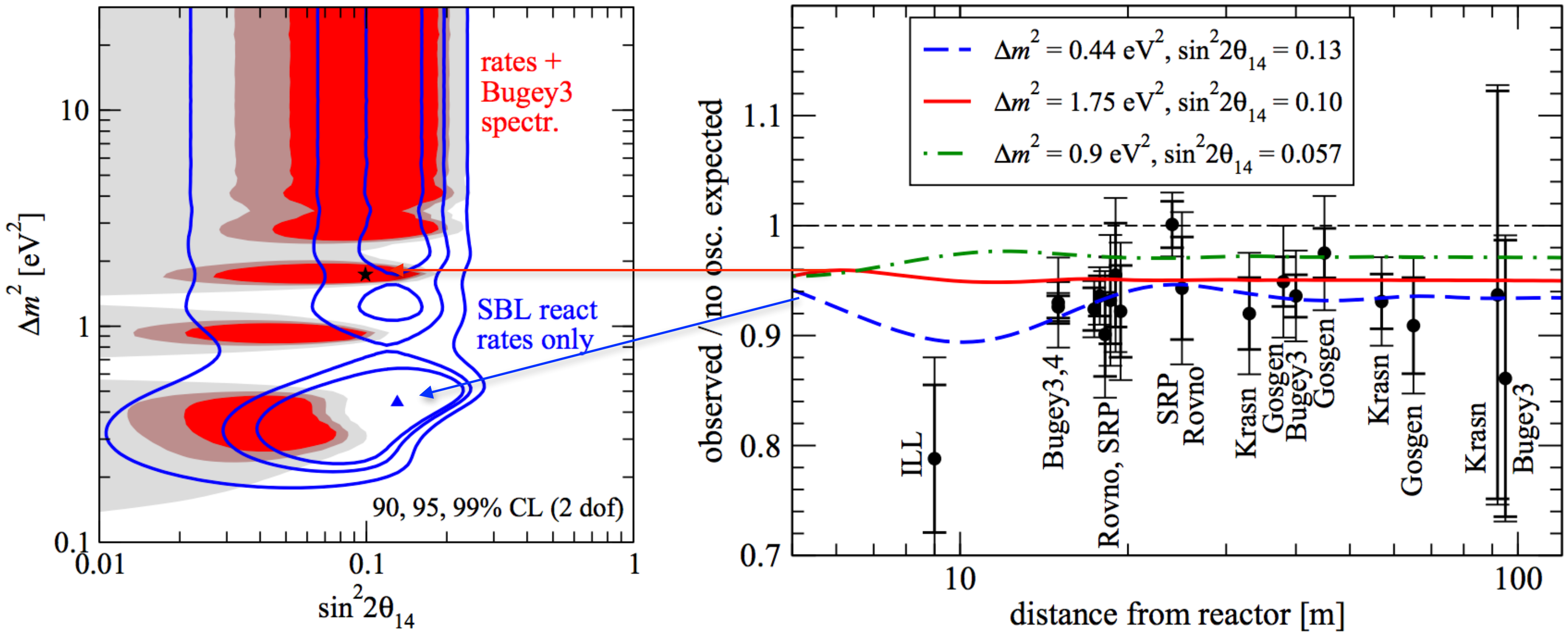
L/E ~ 2-3 m/MeV   L/E ~ 25-30 m/MeV



Curves show fits to data assuming standard 3 neutrino oscillations and assuming oscillations with one additional sterile neutrino

$$\bar{\nu}_e \rightarrow \nu_x$$

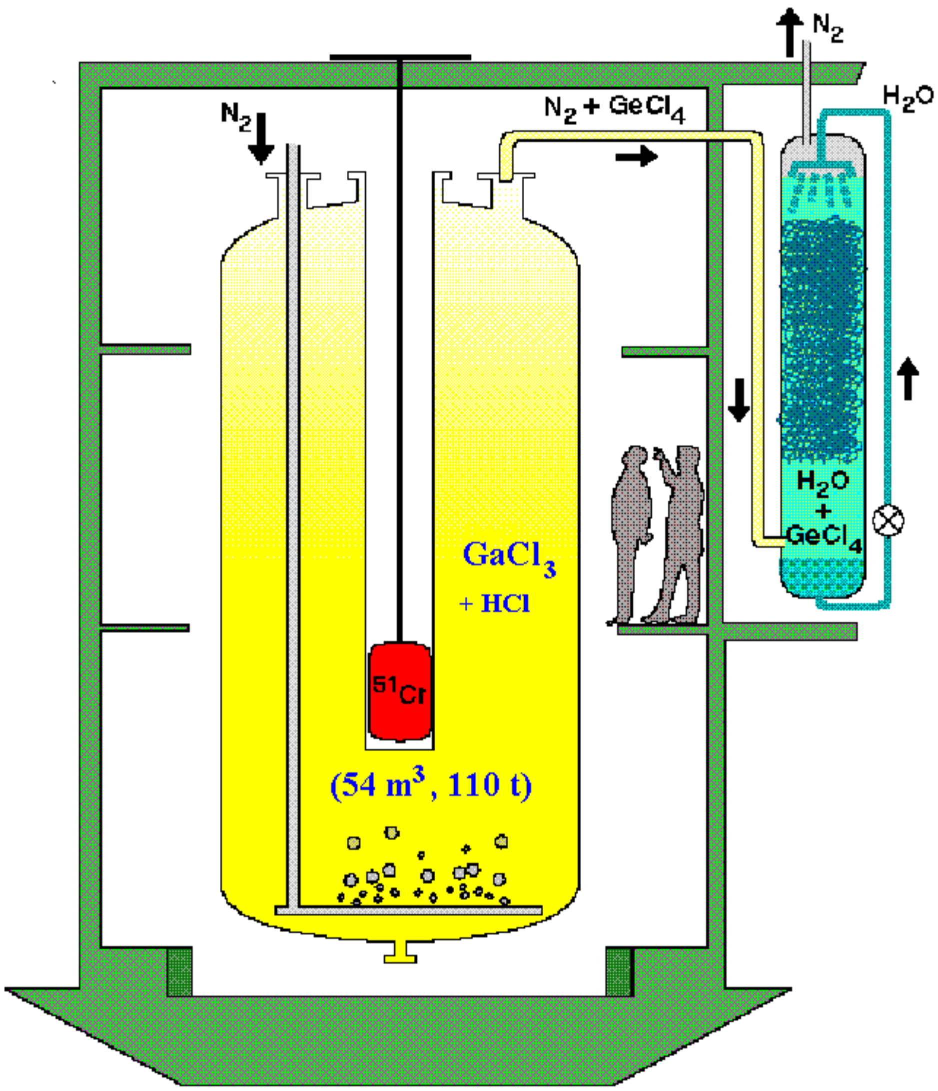
Reactor Antineutrino Anomaly



- Global fit to reactor data from J. Kopp et al. “Sterile Neutrino Oscillations: the global picture”, arXiv:1303.3011 (2013).
- Best fit ratio found to be 0.935 ± 0.024 indicating a 6.5% deficit at short baseline.

GALLEX and SAGE Source Calibration

- GALLEX and SAGE measured solar neutrino rates well below the prediction (now known to be oscillations)
- To understand their absolute efficiencies, they calibrated their detectors with low energy neutrino sources - running with Cr-51 or Ar-37 sources
    - Cr-51 produces 750 keV (90%) and 430 keV (10%) neutrinos
    - Ar-37 produces an 811 keV neutrino
- This amounts to an experiment with very low energy neutrinos (100s keV) over a very short baseline (~1-few meters)

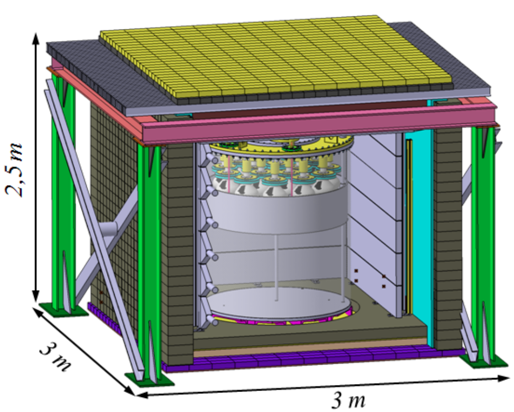


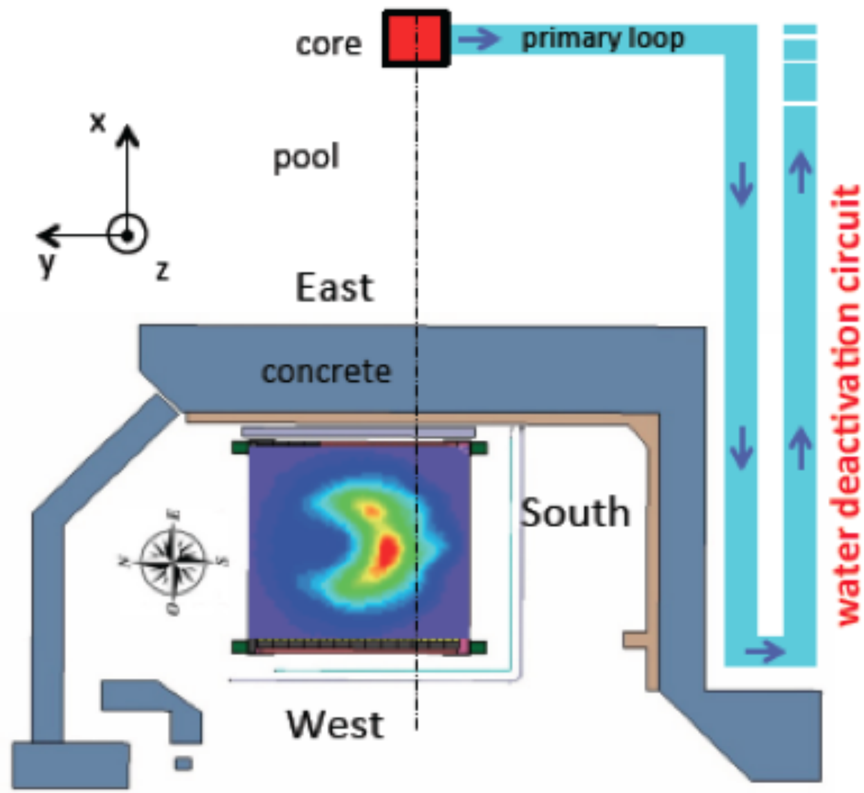
GALLEX

Backgrounds Present a Huge Challenge

Huge unexpected reactor-on background from water deactivation circuit. Lesson for future experiments:
It is critical to measure and understand backgrounds at detector site.

Nucifer





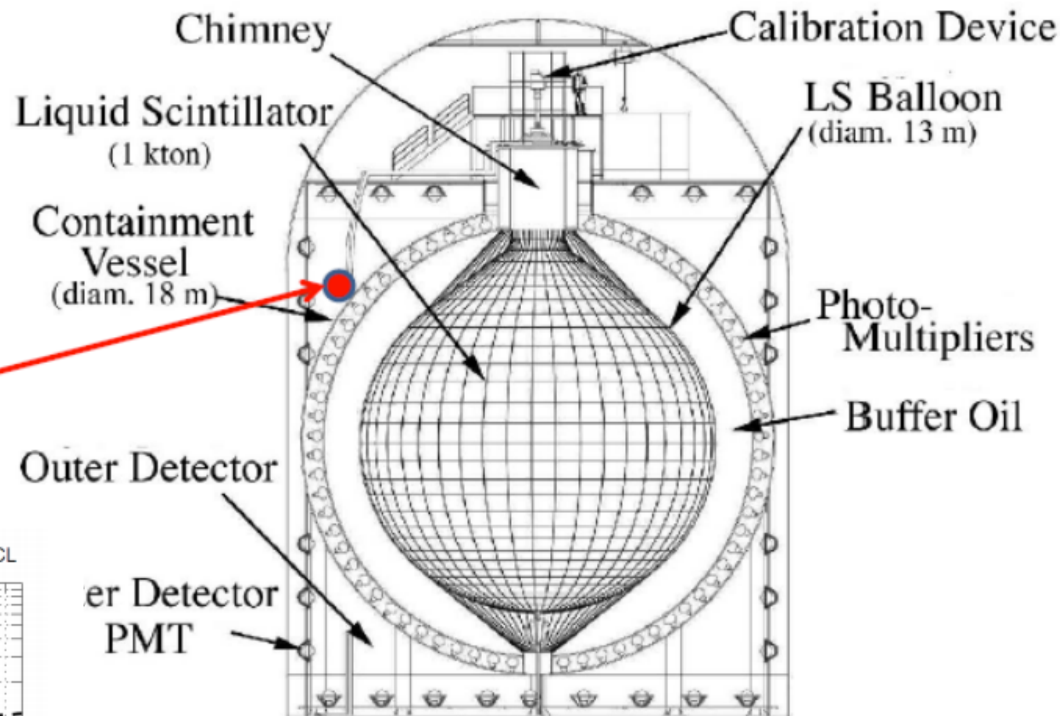
Barycenters of the PMT's charges

Radioactive Source Experiments

- Potentially fast and relatively inexpensive way to pursue sterile neutrino oscillations
- Largely because these experiments use existing neutrino detectors
- Both neutrino sources ^{51}Cr (chromium) and antineutrino sources ^{144}Ce-^{144}Pr (cerium-praseodymium) are being considered

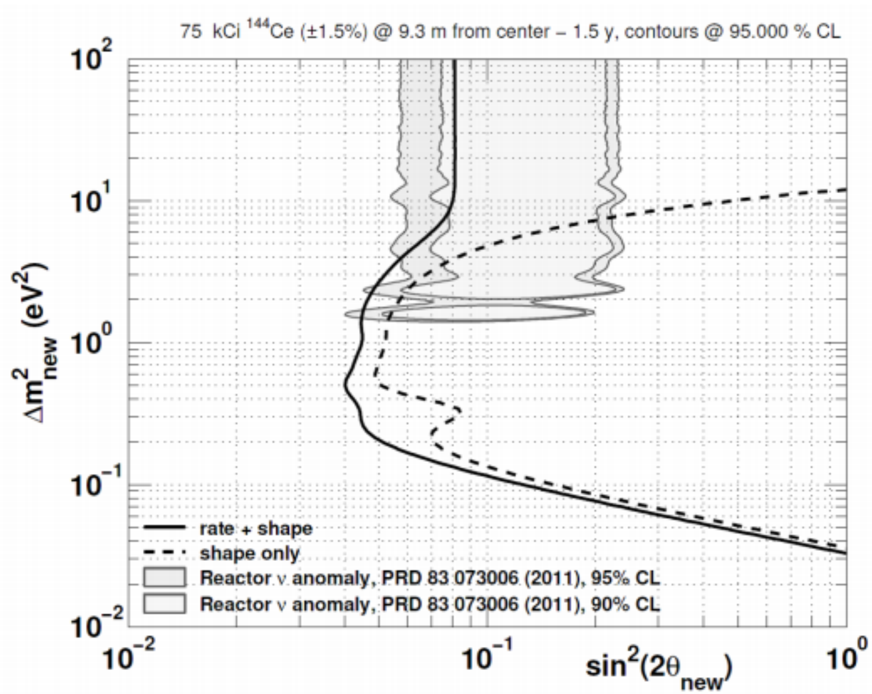
CeLAND Source Experiment

Place an antineutrino source in outer detector region of KamLAND



$^{144}Ce - ^{144}Pr$ source

A. Gando et al., arXiv:1309.6805



95% contours shown for 1.5 years of data

Sensitivity at high Δm^2 depends on knowing absolute intensity of source

Source Experiment at Borexino (SOX)

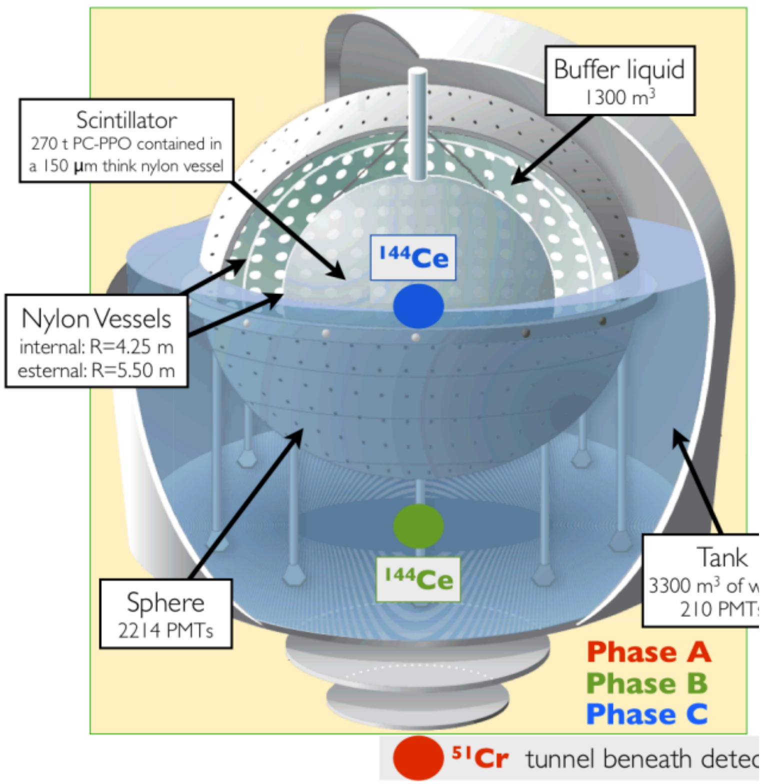
G. Bellini et al., arXiv:1304.7721

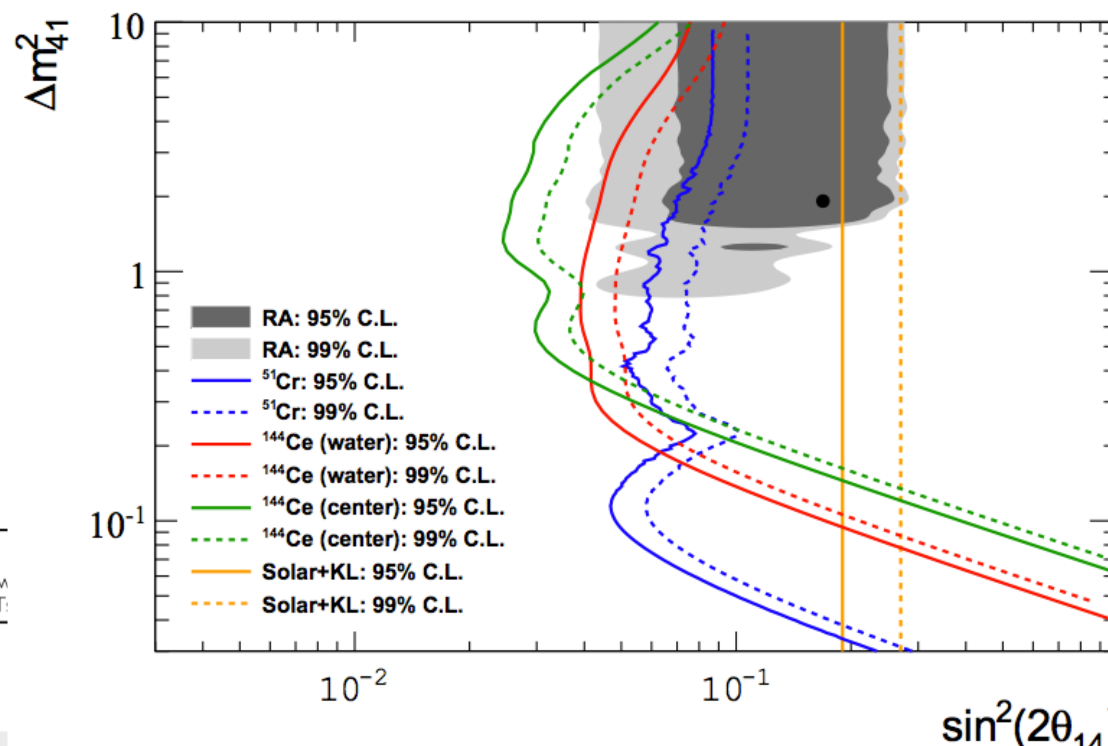
- Use well known neutrino ^{51}Cr source
- Or antineutrino ^{144}Ce-^{144}Pr source
- With a well understood detector

^{51}Cr neutrinos: E_ν = 750 keV

^{7}Be neutrinos: E_ν = 787 keV

liquid scintillator detector

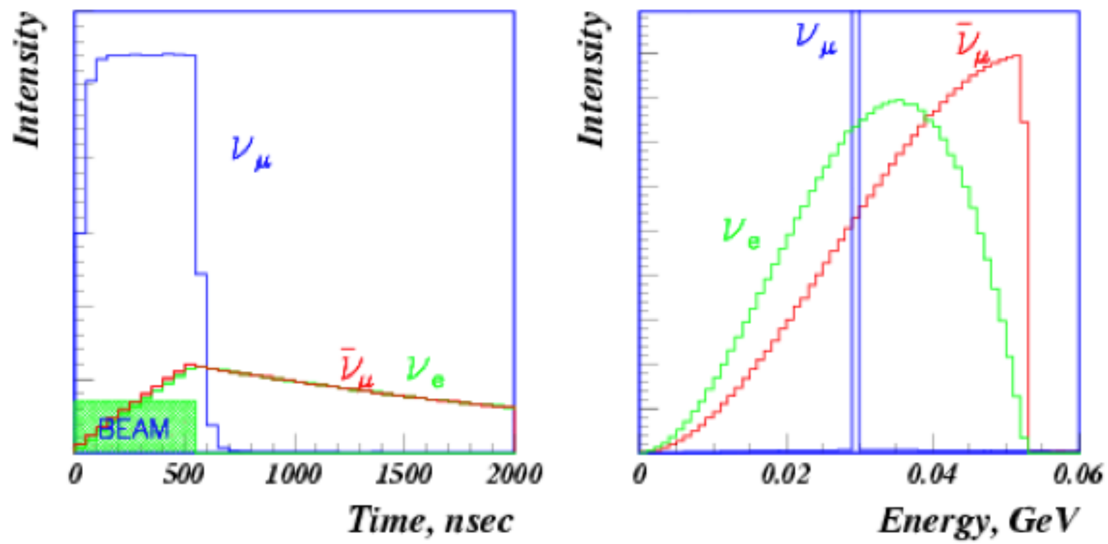




Location matters

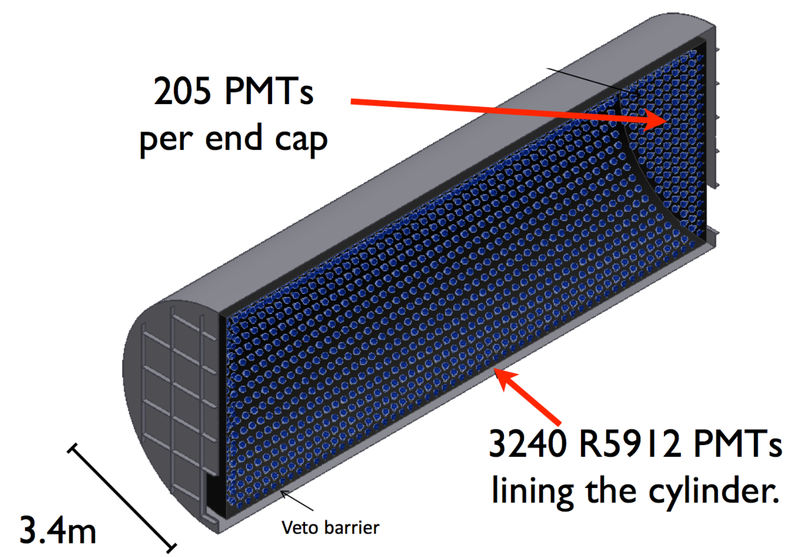
Decay-At-Rest Source Experiments

- Decay-At-Rest sources provide large, well-understood neutrino fluxes
- High-statistics could allow experiments to observe the characteristic L/E shape across a detector
- π Decay-At-Rest
  - OscSNS experiment
- K Decay-At-Rest
- Isotope Decay-At-Rest
  - IsoDAR experiment



The OscSNS Experiment

- Make use of the “free” neutrino source at the Spallation Neutrino Source (SNS) at Oak Ridge NL
- $2x10^{23}$ protons on target per year
- Build a neutrino detector near the source

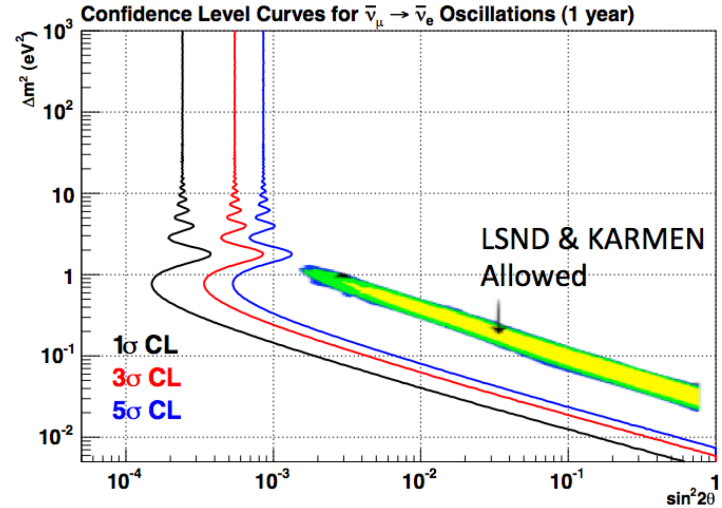


The OscSNS Experiment

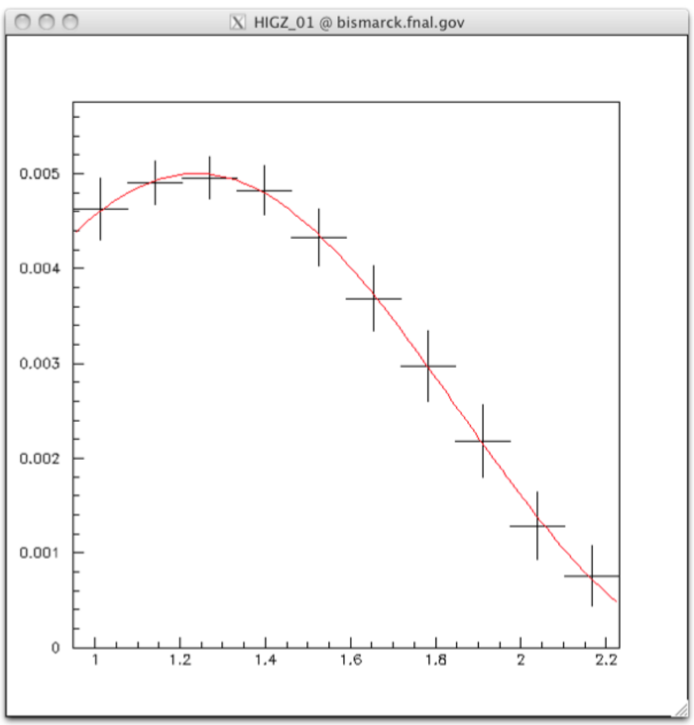
- Compared to LSND
  - Mass 5x larger
  - Neutrino source intensity 2x greater
  - Duty factor 1000x smaller (less cosmogenic background)
  - Negligible decay in flight by putting detector behind the proton target
  - Separation of ν_μ and $\nu_e/\bar{\nu}_\mu$ by timing
  - Expect 350 $\bar{\nu}_e$ oscillation events per year with 80 background events

The OscSNS Experiment

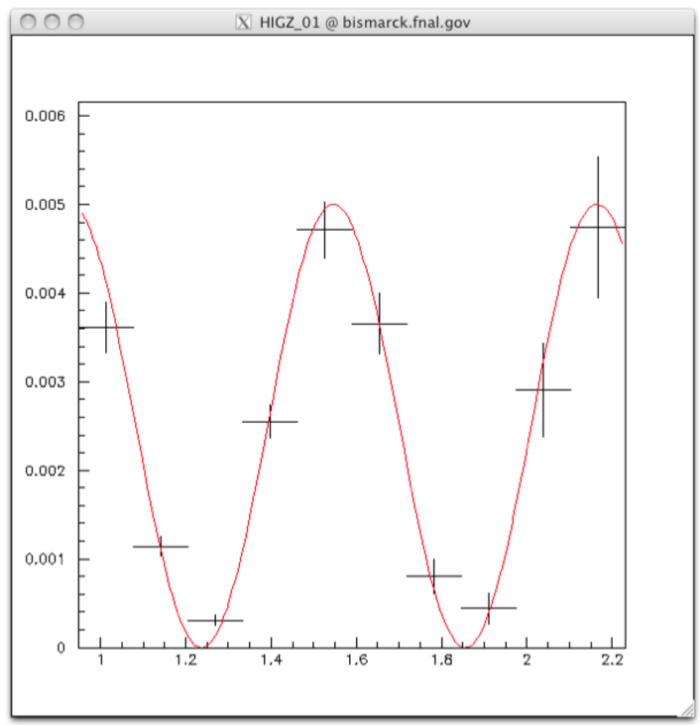
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$



Assuming 10y of data & $\sin^2 2\theta = 0.005$, $\boxed{\Delta m^2 = 1\ \text{eV}^2}$



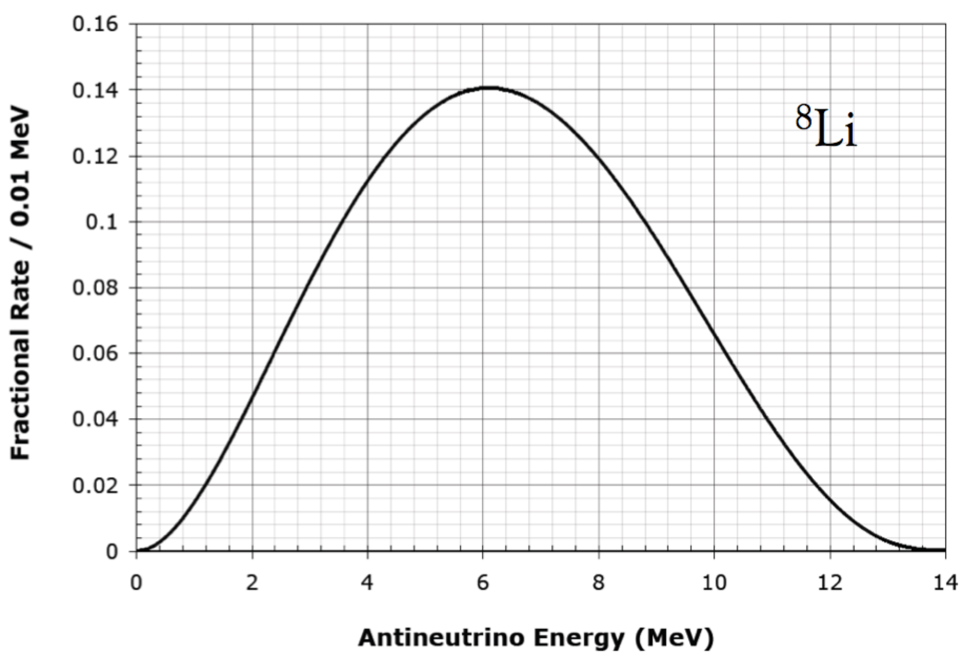
Assuming 10y of data & $\sin^2 2\theta = 0.005$, $\boxed{\Delta m^2 = 4\ \text{eV}^2}$



L/E (m/MeV)

The IsoDAR Experiment

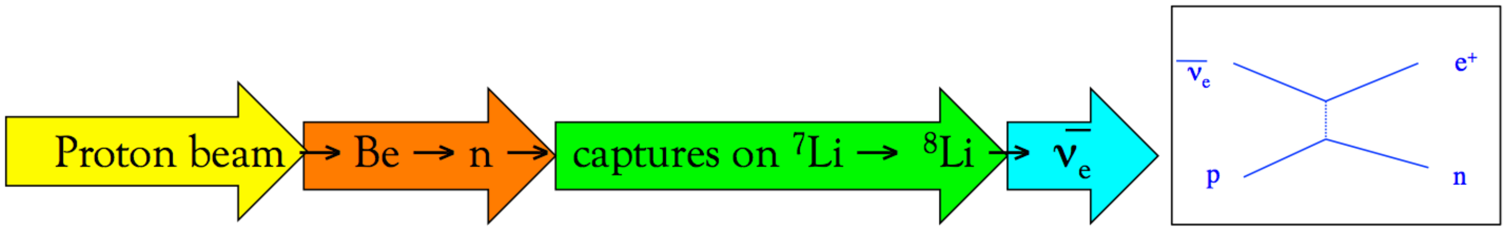
- The beta-decay-at-rest of ^{8}Li isotope produces $\bar{\nu}_e$ above 3 MeV
- Need to make a lot of ^{8}Li close to an underground detector that can see inverse beta decay

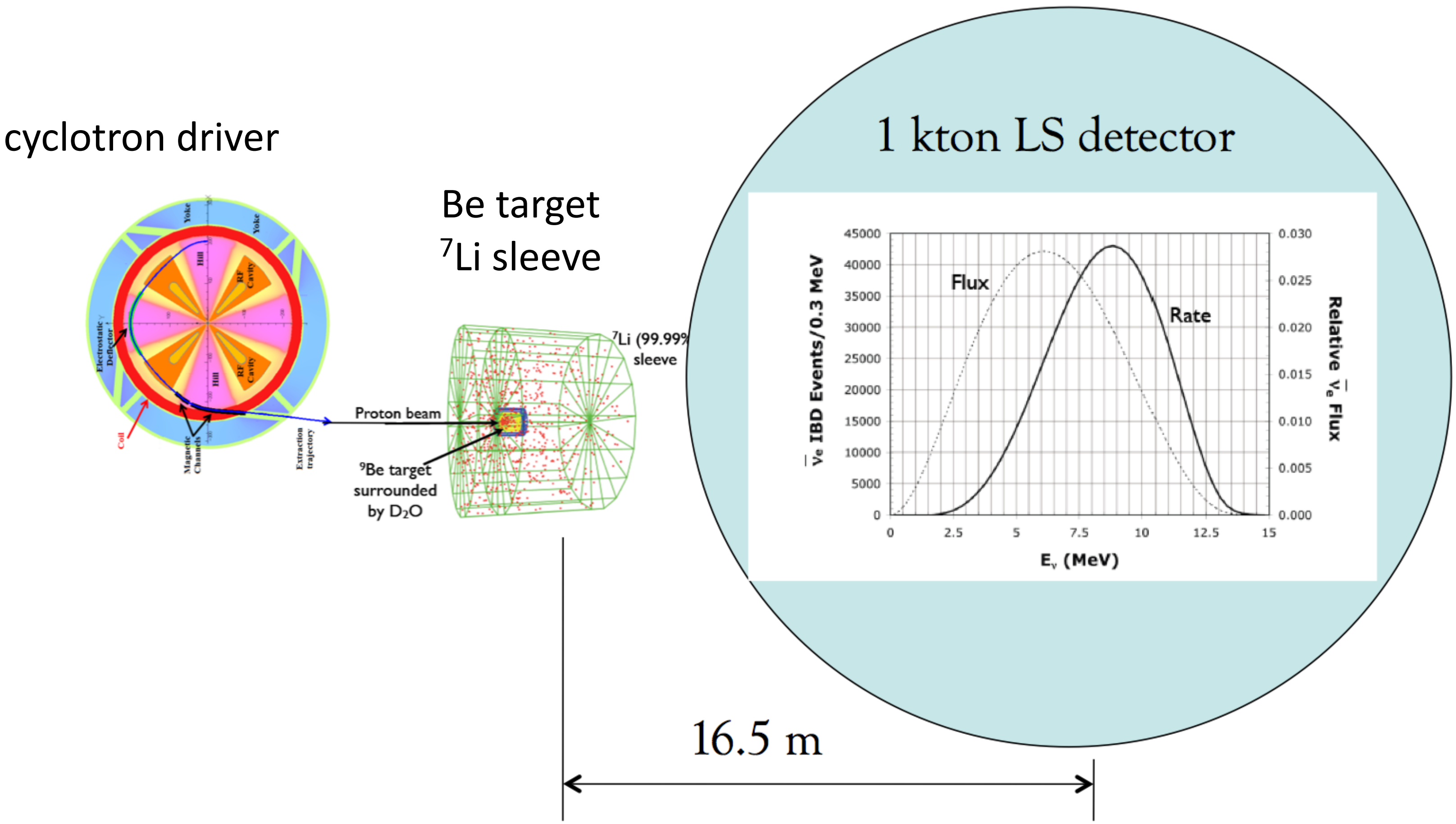


But only a few isotopes have endpoints > 3 MeV, above environmental backgrounds that affect detectors.

e.g.
$^{8}Li \rightarrow {}^{8}Be + e + \bar{\nu}_e$

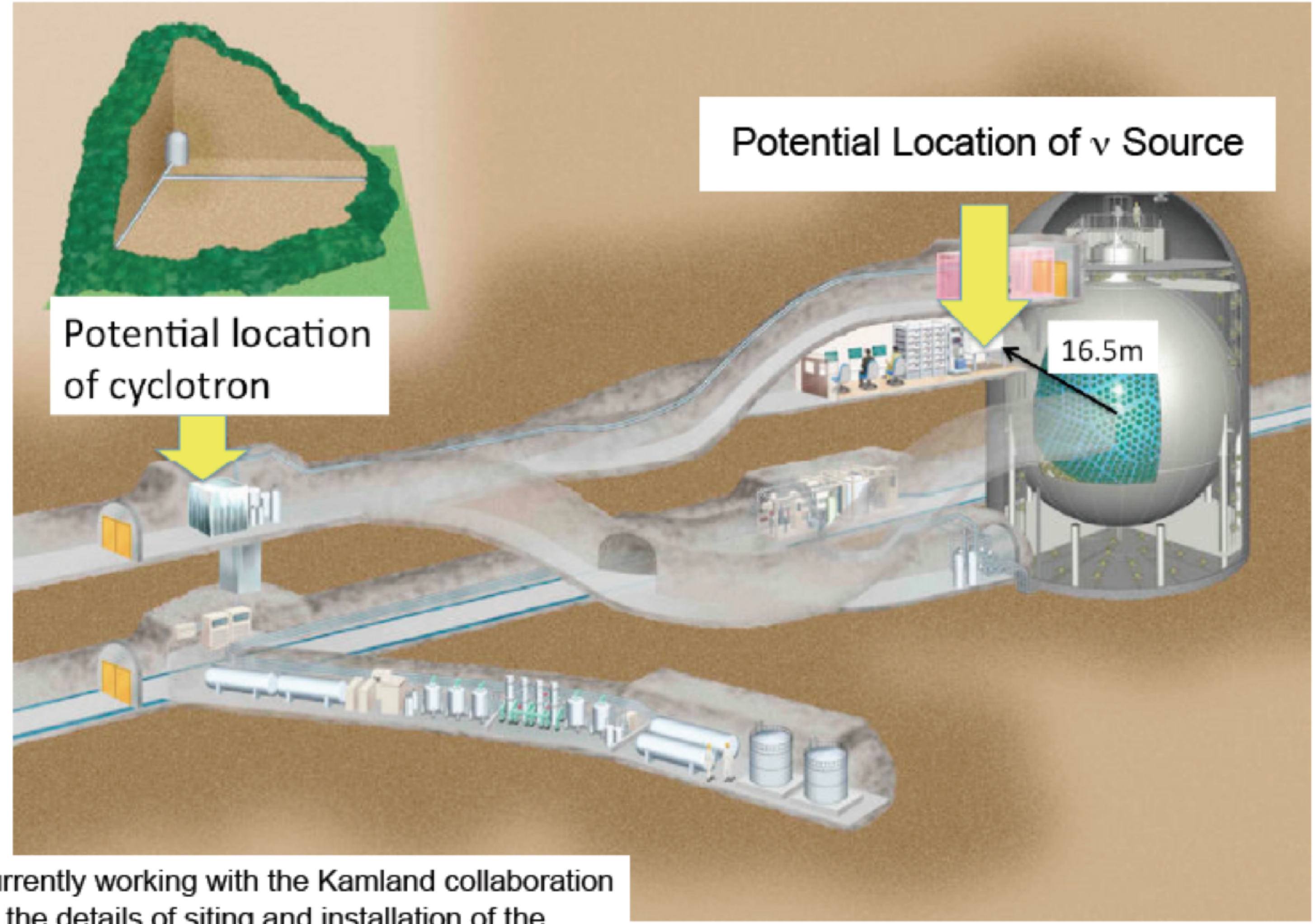
The IsoDAR Experiment





The IsoDAR Experiment

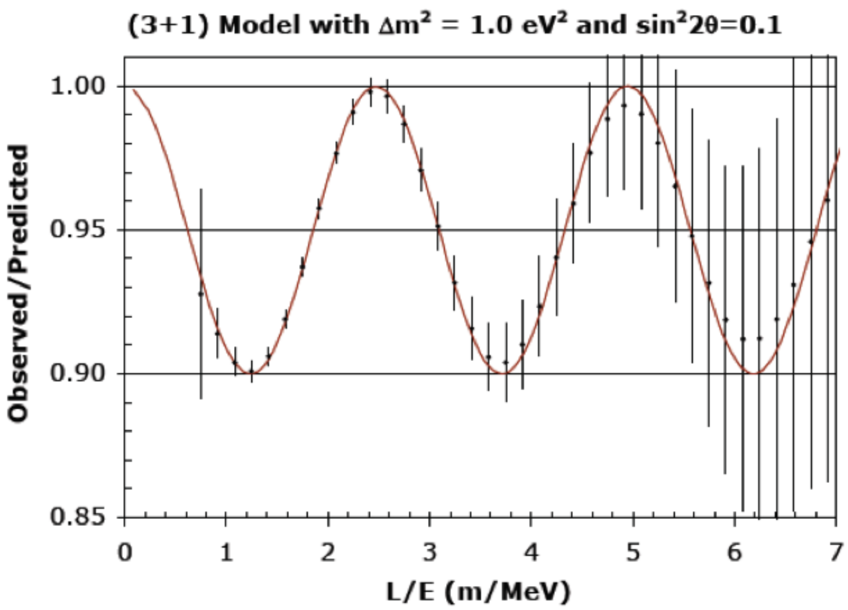
KamLAND would work perfect



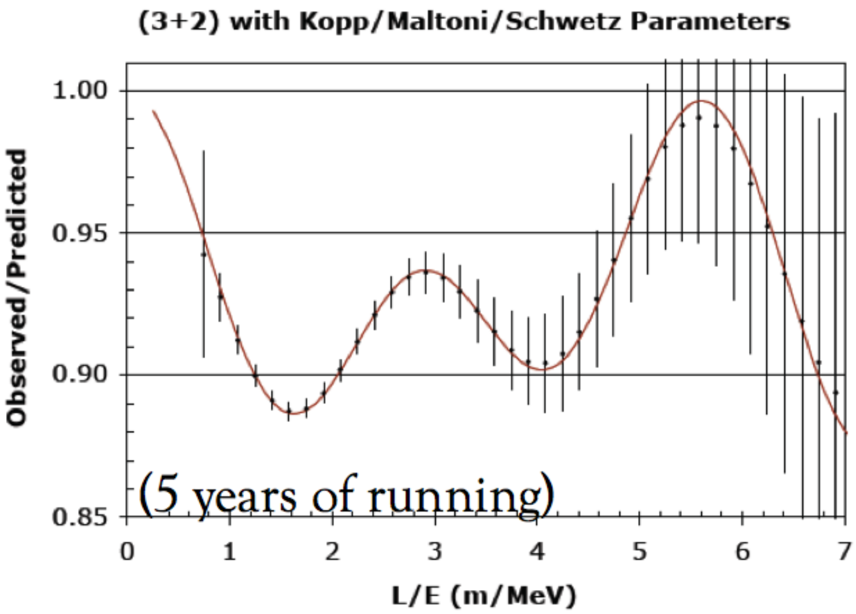
Currently working with the Kamland collaboration on the details of siting and installation of the cyclotron, beamline, and neutrino source.

The IsoDAR Experiment

3+1

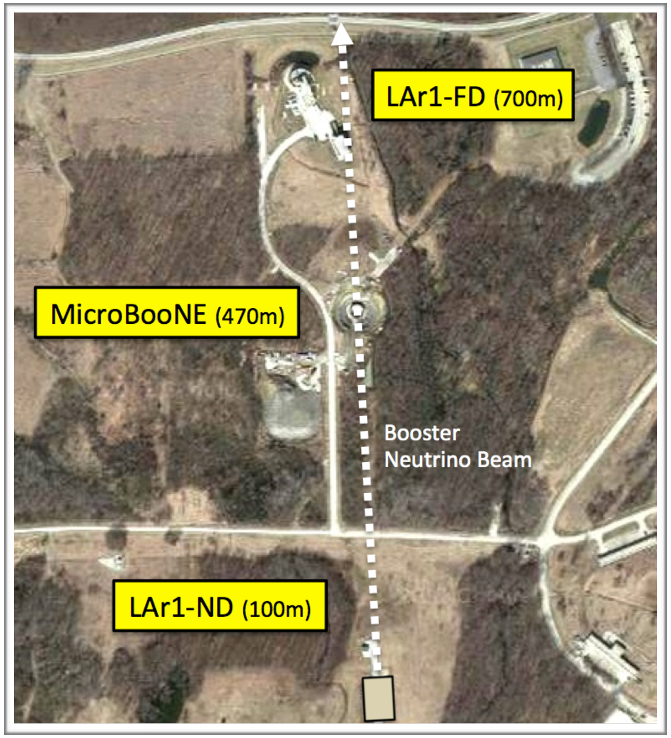


3+2

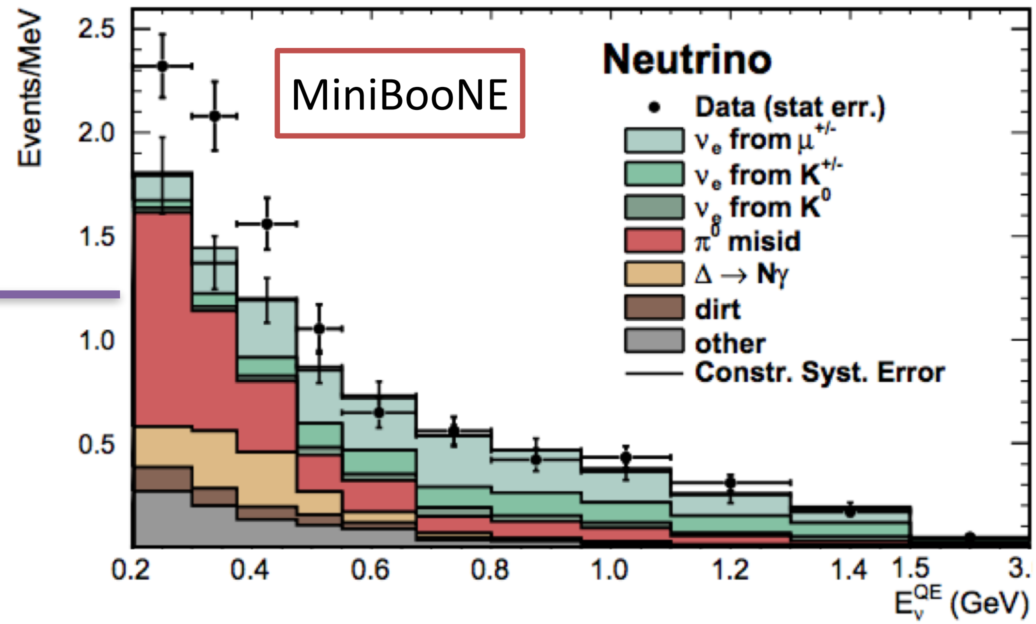


Possibility to distinguish between 1 and multiple sterile neutrino models through oscillation pattern!

Check Length Dependence of Excess



A. A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. 110 161801 (2013)



MicroBooNE

By scaling directly from observed rates in MiniBooNE, MicroBooNE expects to see ~50 background and 50 excess events in 6.6x10^{20} POT run

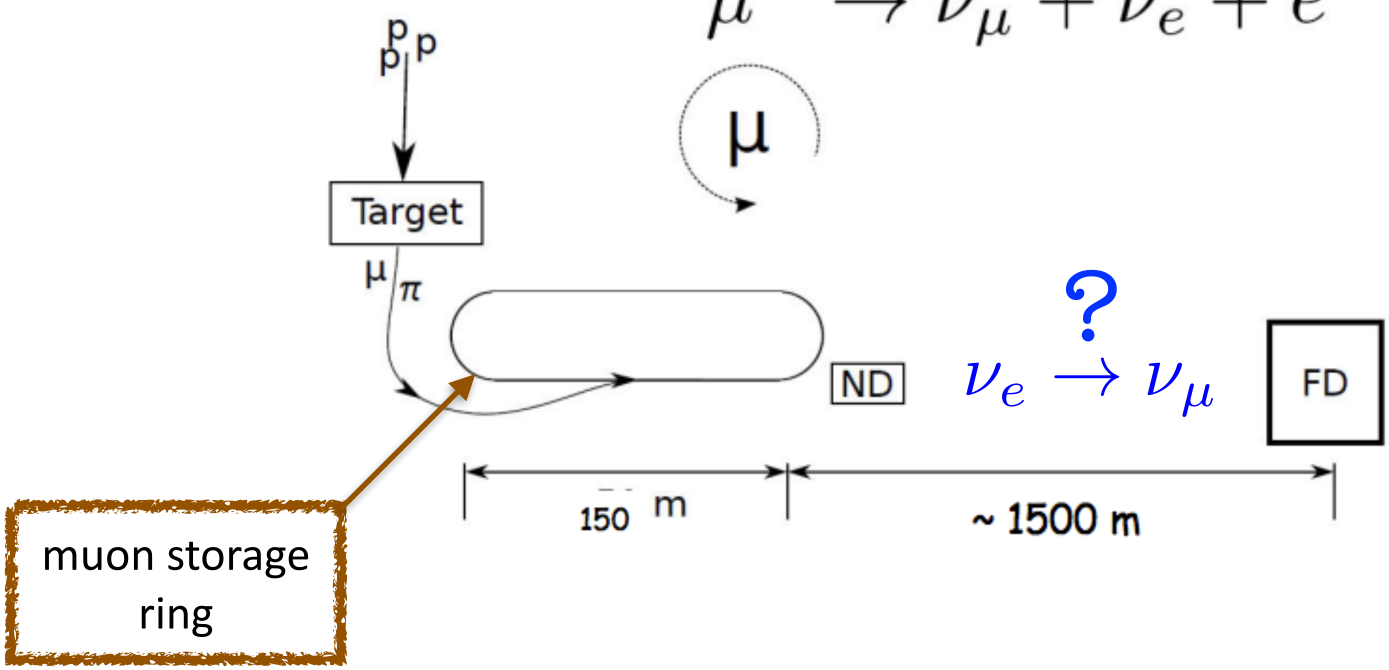
Near Detector

Assuming NO L/E dependence LAr1-ND would expect to see ~320 background and 300 excess events in 2.2x10^{20} POT run

NuSTORM

- Muon storage ring, decay-in-flight produces very well understood neutrino beam of ν_e and $\bar{\nu}_\mu$
- Look for oscillations through $\nu_e \rightarrow \nu_\mu$ appearance!
- Best sensitivity going for 3+1 sterile model due to huge rate and low backgrounds for muon neutrino appearance

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$



NuSTORM

$$\nu_e \rightarrow \nu_\mu$$